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UNIVERSITY OF ALBERTA

PERSONAL SCIENCE AND ITS IMPLICATIONS FOR SCIENCE EDUCATION:

REFLECTIONS ARISING FROM A COMBINED PROJECT IN SCIENCE EDUCATION AND ASTRONOMY

BY

BRIAN E. MARTIN ©

A THESIS
SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND
RESEARCH IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR
THE DEGREE OF DOCTOR OF PHILOSOPHY
in
SCIENCE EDUCATION AND ASTRONOMY

DEPARTMENT OF SECONDARY EDUCATION

EDMONTON, ALBERTA

SPRING, 1990

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Brian Martin

Brian Martin
Site 6, Box 2, RR 8
Edmonton, Alberta
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Date: April 24, 1990

Where were you when I laid the earth's
foundation?
Tell me if you understand. ...
Can you bind the beautiful Pleiades?
Can you loose the chords of Orion?
Can you bring forth the constellations in
their seasons
or lead out the Bear with its cubs?
Do you know the laws of the heavens?
(Job:38:4, 31-33)

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THE UNDERSIGNED CERTIFY THAT THEY HAVE READ, AND RECOMMEND TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH FOR ACCEPTANCE, A THESIS

ENTITLED PERSONAL SCIENCE AND ITS IMPLICATIONS FOR SCIENCE EDUCATION: REFLECTIONS ARISING FROM A COMBINED PROJECT IN SCIENCE EDUCATION AND ASTRONOMY

SUBMITTED BY BRIAN E. MARTIN
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

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Date: April, 20, 1990

Dedication

This dissertation is dedicated to the memory of my brother

Dwight Kenneth Martin (1943-1974)

who awakened my interest in the stars and always encouraged my efforts.

Abstract

A combined study in Astronomy and Science Education was undertaken to explore the personal dimension of science within research and science education. The term "personal science" has been introduced to embrace a host of personal factors unavoidably present in the pursuit of science. The primary goal of this thesis is to demonstrate the reality of personal science within my researching as an astronomer and to argue that the notion of personal science must play a significant role in our thinking about science education. The thesis develops in two sections:

Part A of the thesis, found in Chapters 1 - 7, focuses on the impact that personal science should have on science education. In this section the diversity implied by the term "science" as it is presently used within science education discourse is considered and it is argued that the idea of personal science should be an essential dimension of school portrayals of science.

In developing the idea of personal science a number of influential philosophies of science have been considered in light of my own experience as an astronomer and teacher. Attention is given to Holton's thematic analysis of science and Polanyi's philosophy of personal knowledge and it is argued that Polanyi's conception of personal knowledge may be used to found a more effective epistemology for science education.

The problem of fostering, communicating and sharing one's personal science is addressed. The suggestion is made that a curriculum focused on one's personal experiencing of the ideas will be more effective in portraying the personal dimension of science. Narrative and story-telling are explored as effective means of communicating and sharing one's personal science.

Part B of the thesis presents the results of three research projects in astronomy. The first project is the observation and analyis of the ellipsoidal binary system 42 Persei and presents the first known model for this system. The second project describes participation in an international collaborative effort to measure the modes of oscillation for two Delta-Scuti variable stars. The third project describes the search for rapid variability within a group of selected A type stars.

Acknowledgement

A thesis has a way of dominating not only the life of its author but also of those unfortunate enough to have to live with the author! It is fitting, then, to express my loving appreciation to my children Nathaniel, Leah, Bronwyn and Nigel and especially to my constant and dearest friend, my wife Evelyn. Without their continual support and patience this thesis could not have been completed and together we wish to thank the following people.

The two principal supervisors of this work, Dr. W. Brouwer and Dr. D.P. Hube have had a deep and formative influence on this thesis. Wytze's steadfast confidence in the project, his good humour, wisdom, patience and above all - friendhsip have been a continual source of encouragement. To you Wytze, a heartfelt thanks. No less appreciated is Doug Hube's equally patient and good humoured support for this project and his keen eye for important detail - not only in the research but also in the reporting of the research. As well, I wish to express a deep appreciation for the very real trust that Doug extended to me. Without this bond of trust the astronomical part of the project simply could not have been done. Both Doug and Wytze embody many of the traits of the exemplary teacher alluded to in this thesis. Thank you.

Dr. H. Kass has also been a continual and probing supporter of this study. Heidi's ability to see past the superficial and get at the meat of the matter has kept before me the challenge of asking "so what?" of many parts of the thesis. Her keen sense of what works and what doesn't has helped shape my thinking about science education and has left an important mark on this thesis and my approach to science education research. To you Heidi, a heartfelt thank you.

Dr. M. VanManen has had an important role to play in this thesis. From Max I acquired a deepened appreciation for the incantive power of the word and was introduced to the phenomenological approach to pedagogic theorizing. The influence of these ideas has had a profound and unifying influence on both the form and content of this thesis. Max has also challenged me to examine my own understanding of and participation in what it means to teach. For this, Max, a sincere thank you.

Many friends and colleagues deserve thanks as well. To Dr. Peter Mahaffy and David Lyder a special thank you for a willingness to share and discuss ideas related to this thesis. Your genuine support and interest has played an important role in this work.

Finally I would like to express my appreciation to the Department of Secondary Education, University of Alberta for making a combined project of this nature possible and to the Social Sciences and Humanities Research Council of Canada (award # 453-870329) for financial support for part of this project.

Table of Contents

Part A 1
Personal Science and Its Implications for Science Education

Chapter One: The Central Questions

1.1 Introduction 2
1.2 The Many Meanings of the Term 'Science' 3
1.3 Structure of this Study and Thesis 5
1.4 Chapter by Chapter Summary of the Thesis 5
1.5 Some Specific Educational Concerns of this Study 7
1.6 Limitations and Possible Strengths of the Study 9
Notes Chapter One 11

Chapter Two: Authentic Science - a Diversity of Meanings

2.1 Introduction 12
2.2 The Many Faces of Science 13
  2.2.1 Methodologic Fidelity 14
  2.2.2 Epistemological Considerations 15
    i. The Presuppositionalists 16
    ii. The Falsificationists 16
    iii. The Hedonists 17
  2.2.3 Personal Science 18
  2.2.4 Private Science 19
  2.2.5 Public Science 20
    i. Popper's Third World of Objective Knowledge 20
    ii. Arguments Against Popper's Third World Hypothesis . . .21
  2.2.6 Historical Science 23
  2.2.7 Societal Science 24
  2.2.8 Technological Science 25
  2.2.9 The Aims of Science 25
2.3 Layers of Experience 27
2.4 An asymptotic approach to authentic science 29
Notes Chapter Two 31

Chapter Three: Personal Science

3.1 Introduction 34
3.2 Holton's Thematic Analysis of Science 36
3.3 The Nature of Themata 45
3.4 Objectivity 49
3.4 Tacit Knowing 54
3.5 Indwelling 58
3.6 Conclusion 59
Notes Chapter Three 60

Chapter Four: The Sharing of Personal Science and the Narrative Element in Science Education

4.1 Introduction 65
4.2 The Aesthetic Mode of Knowing in Science Education . . . 66
4.3 The Use of the Narrative Mode 69
4.4 Areas in Which the Narrative Mode May Prove Most Effective in the Teaching of Science 71
  4.4.1 Methodologic Aspects 72
  4.4.2 Epistemological Considerations 72
  4.4.3 Personal and Private Science 74
  4.4.4 Public Science 76
  4.4.5 Historical Science 76
  4.4.6 Societal and Technological Science and the Aims of Science 79
4.5 Conclusions 81
Notes Chapter Four 83

Chapter Five: Astronomical Investigations

5.1 Introduction 85
5.2 My Research Within the Broader Scope of Modern Astronomy 85
5.3 Some Basic Ideas About Stars 86
5.4 Astronomical Photometry 90
5.5 Differential Photometry 92
5.6 Photometric Systems 92
5.7 The Ellipsoidal Variable 42 Persei - A Close Binary Star . . 93
5.8 Light Curves for 42 Persei 97
5.9 A Possible Model for 42 Persei 100
5.10 The Significance of the Research on 42 Persei 104
5.11 The Study of Delta Scuti Variable Stars 107
5.12 The Cause of Stellar Pulsation 109
5.13 The Detection of Multi-Mode Oscillations in δ-Scuti Stars The International Campaign 111
5.14 The Search for Rapidly Oscillating Peculiar A Stars - a "Failed" Project 114
5.15 The Variability of HD73819 and Serendipity in Science . . 118
5.16 Conclusions 120
Notes Chapter Five 122

Chapter Six: Exploring One's Personal Science

6.1 Introduction 123
6.2 Pedagogic Links 123
6.3 What's a Falling Star? 125
6.4 Trust 126
6.5 All in a Night's Work 129
6.6 Force of Habit 133

6.7 I Bring Myself to the Data 135
6.8 Midnight Conversations with Tom 140
6.9 There are no Green Stars 142
6.10 Satisfaction 144
6.11 Doubt 147
6.12 Conclusions 153
Notes Chapter Six 155

Chapter Seven: Conclusion: The Educational Implications of Personal Science 157

7.1 Introduction 157
7.2 The Epistemology of School Science 157
7.3 Personal Science and its Relation to Constructivist Models of Science Education 163
7.4 Science Education Centered on Personal Science 167
7.5 Indwelling and the Growth of Personal Science 172
7.6 A Society of Explorers 175
7.7 Some Conclusions and Future Avenues of Research 177
7.8 Some Personal Reflections on the Research 180
Notes Chapter Seven 181

Part B Astronomical Investigations 185

Chapter Eight: The Ellipsoidal Variable 42 Persei: Observations and Model

8.1 Introduction 186
8.2 The Basic Theory of Ellipsoidal Variable Stars 186
    8.2.1 The Roche Model 187
    8.2.2 Brightness Variation Due to Projected Surface Area . . 193
    8.2.3 Limb Darkening, Gravity Darkening and Reflection . . . 193

8.3 The Data 195
    8.3.1 Data Reduction Methods Used in This Study 196
    8.3.2 Transformation to the UBV Standard System 201
    8.3.3 The Photometric Variation 208
    8.3.4 Radial Velocities 218
    8.3.5 Orbital Elements 218
8.4 The Simple Model 219
8.5 The Wilson-Devinney Solution 226
8.8 Conclusions 234
Notes Chapter Eight 241

Chapter Nine: Observations and Analysis of the Delta Scuti Stars HR 729 and KW 207

9.1 Introduction 242
9.2 The Frequency Analysis of d-Scuti Light Curves 243
    9.2.1 The Problem of Aliasing 243
    9.2.2 The False Alarm Criterion for Fourier Transforms . . 255
9.3 The International Campaigns on HR 729 and KW 207 . . . 259
    9.3.1 The Campaign on HR 729 259
        9.3.1.1 Observing Protocol for HR 729 260
        9.3.1.2 Frequency Analysis for HR 729 260
    9.3.2 The Campaign on KW 207 273
        9.3.2.1 Observing Protocol for KW 207 273
        9.3.2.2 Frequency Analysis for KW 207 279
9.4 Interpretation of the Analysis for HR 729 and KW 207 292
    9.4.1 Stellar Pulsation - an Overview 292
    9.4.2 Frequency Identification for HR 729 and KW 207 . . 299
9.5 Conclusions 304
Notes Chapter Nine 306

Chapter Ten: A Search for Rapid Variability in Peculiar A Type Stars

10.1 Introduction 308
10.2 The Program Stars 309
10.3 Method of Observation 309
10.4 Methods of Analysis 311
10.5 Summary of the Observations 311
  10.5.1 HD 32655 311
  10.5.2 HR 1971 315
  10.5.3 HR 478, HR 707, HR 1974, HR 2564, and HD 43244 315
10.6 Conclusions 315
Notes Chapter Ten 320

Epilogue

Personal Reflections on Science Teaching 321
Future Directions of This Research 324
Bibliography 325

List of Tables

Table 5.1 Simple model, derived from Morris' approximations, for the close binary system 42 Persei 101

Table 5.2 Model for 42 Persei derived from application of the Wilson-Devinney modeling code. 102

Table 8.1 U,B and V filter transformation coefficient data derived from measures of five Pleiades standard stars on February 17, 1989. 203

Table 8.2 Regression analysis for the UBV transformation coefficients. Analysis based on data given in Table 8.1. 204

Table 8.3 UBV data for (42 Persei - HR 1164) phased in intervals of width 0.01. 209

Table 8.4 Fourier coefficients from a fourth order fit for the photometric variation of 42 Persei. 210

Table 8.5 Radial velocity data for 42 Persei. 220

Table 8.6 Spectroscopic solution for 42 Persei. 221

Table 8.7 Family of solutions to equations 8.18 - 8.21 suggesting possible model parameters for 42 Persei. 224

Table 8.8 Solution for 42 Persei based on LC output from the Wilson-Devinney code. 236

Table 9.1 Table of frequencies and amplitudes for the δ Scuti star 4 Canes Venatici, taken from Breger et al, October 1989. 253

Table 9.2 Table of frequencies and amplitudes for the δ Scuti star 4 Canes Venatici based on a simulated data set. 257

Table 9.3 Summary of data for the δ Scuti variable HR 729 and the comparison stars HR 646 and HR 741. 262

Table 9.4 Journal of observations for November 1988 campaign on HR 729. 266

Table 9.5 Possible frequency solution for HR 729.1 mmag. 272

Table 9.6 Summary of data for the δ Scuti variable KW 207 and the comparison stars KW 276 (C1) and KW 348 (C2). 277

Table 9.7 Journal of observations for the February campaign on KW 207. 278

Table 9.8 Possible frequency solution for KW 207. 287

Table 9.9 Provisional frequency-amplitude solution for KW 207 based on data collected at the Devon Astronomical Observatory during the February 1989 international campaign on the δ Scuti star KW 207. 291

Table 9.10 Table of typical Q values for a δ Scuti variable M = 2 MO, log Teff = 3.88, Mbol = 1.207. 295

Table 9.11 Pulsational Q values for HR 729 and KW 207. 301

Table 9.12 Mode identification for HR 729 and KW 207. 305

Table 10.1 The program stars used in the search for rapid oscillations. 310

Table 10.2 Summary of observations of HD 32655. 312

Table 10.3 Summary of observations of HR 1971. 316

Table 10.4 Journal of observations for HR 478, HR 707, HR 1974, HR 2564 and HD 43244. 319

List of Figures

Figure 3.1 Holton's proposition space. 38

Figure 3.2 Proposition space augmented by the thematic dimension of scientific ideas. 44

Figure 5.1 The Hertzsprung-Russell diagram. 87

Figure 5.2 The luminosity classes lying on the Hertzsprung-Russell diagram. 89

Figure 5.3 A close binary system. 95

Figure 5.4 Photometric variation of 42 Persei in the U, B and V filter regions. 98

Figure 5.5 A comparison between the observed V filter light curve for 42 Persei and the one predicted by the WD modeling code. 103

Figure 5.6 V filter light curve for the δ Scuti star KW 207. 112

Figure 5.7 Nonradial modes of oscillation on a stellar surface for different values of l and m. 115

Figure 5.8 V filter light curve for the star HD 73819 on 4 separate evenings. 119

Figure 6.1 Light curves for the stars HD 32655 and HD 85040 (= 20 Leonis). HD 85040 is a known δ Scuti variable. 138

Figure 6.2 Fourier transforms for HD 32655 for the nights: Nov 10/86, Jan 22/87, Jan23/87, Jan24/87 and Jan 25/87. 139

Figure 8.1. A binary system with surrounding Roche equipotential surfaces. 189

Figure 8.2 Graph showing the location of the 3 axial Lagrangian points as a function of mass ratio. 192

Figure 8.3 First order extinction graph for instrumental b magnitude of HR 1164 on the night of February 17, 1989. 198

Figure 8.4 Plot of sky brightness measured in the b filter on the night of February 11, 1989. A least squares cubic spline has been fit to the data. 200

Figure 8.5 Plot of (V - v0) versus (B - V) for selected Pleiades standard stars. 205

Figure 8.6 Plot of (B -V) versus (b - v)0 for selected Pleiades standard stars. 206

Figure 8.7 Plot of (U - B) versus (u - b)0 for selected Pleiades standard stars. 207

Figure 8.8 V filter observations of (42 Persei - HR 1164) phased in bins of width 0.01. 211

Figure 8.9 B filter observations of (42 Persei - HR 1164) phased in bins of width 0.01. 212

Figure 8.10 U filter observations of (42 Persei - HR 1164) phased in bins of width 0.01. 213

Figure 8.11 U,B, and V filter observations and Fourier fits for (42 Persei - HR 1164). 214

Figure 8.12 V filter (O - C) for (42 Persei - HR 1164). 215

Figure 8.13 B filter (O - C) for (42 Persei - HR 1164). 216

Figure 8.14 U filter (O - C) for (42 Persei - HR 1164). 217

Figure 8.15 Radial velocities for 42 Persei. 222

Figure 8.16 Family of possible solutions for 42 Persei based upon simple analytic model of Kopal. 225

Figure 8.17 Wilson-Devinney LC solution (solid line) for the V filter compared to observations. 229

Figure 8.18 Wilson-Devinney LC solution (solid line) for the B filter compared to observations. 230

Figure 8.19 Wilson-Devinney LC solution (solid line) for the U filter compared to observations. 231

Figure 8.20 Wilson-Devinney LC solution in V filter. 232

Figure 8.21 Wilson-Devinney LC solutions in V filter for primary temperatures of 8700, 8900 and 9200 K. 233

Figure 8.22 Wilson-Devinney LC solutions in V filter for secondary temperatures of 3500 K, 5500 K and 6500 K. 235

Figure 8.23 Wislon-Devinney LC solutions in V filter for primary potentials 2.60, 2.65, 2.70, and 2.80. 237

Figure 8.24 Wislon-Devinney LC solutions in B filter for primary potentials 2.60, 2.65, 2.70, and 2.80. 238

Figure 8.25 Wislon-Devinney LC solutions in V filter for secondary potentials 3.0, 3.5, 4.0, 4.5 and 5.0. 239

Figure 9.1 Time domain light curve for $l(t) = 3.0 + 0.145\cos(2\pi 6t) + 0.23\cos(2\pi 8.5t)$. 245

Figure 9.2 Discrete Fourier Transform of $l(t) = 3.0 + 0.145\cos(2\pi 6t) + 0.23\cos(2\pi 8.5t)$. 246

Figure 9.3 The Data windows producing an observed light curve l(t). 249

Figure 9.4 Data and Spectral Windows and Fourier transforms. 250

Figure 9.5 The removal of the spectral window aliases from a simulated data set based on 4 Canes Venatici. 256

Figure 9.6 HR 729 - HR 646 (V - C1) plots for the November campaign on HR 729. 263

Figure 9.7 HR 729 - HR 741 (V - C2) plots for the November campaign on HR 729. 264

Figure 9.8 HR 741 - HR 646 (C2 - C1) plots for the November campaign on HR 729. 265

Figure 9.9 Fourier transforms of V-C1 and V-C2 data for the HR 729 campaign, November 1988. 267

Figure 9.10 Spectral window and removal of prominent spectral features from the V-C1 Fourier transform. 268

Figure 9.11 Spectral window and removal of prominent spectral features from the V-C2 Fourier transform. 269

Figure 9.12 Spectral window and removal of prominent spectral features from the C2-C1 Fourier transform. 270

Figure 9.13 Three frequency fit to the V-C1 data for HR 729. 271

Figure 9.14 KW 207 - KW 276 (V - C1) plots for the February campaign on KW 207. 274

Figure 9.15 KW 207 - KW 348 (V - C2) plots for the February campaign on KW 207. 275

Figure 9.16 KW 348 - KW 276 (C2 - C1) plots for the February campaign on KW 207. 276

Figure 9.17 Power spectrum for the data set V-C1 consisting of 1000 scans in the range 2 - 100 c/d. 280

Figure 9.18 Spectral window and removal of prominent spectral features from the V-C1 Fourier transform. 281

Figure 9.19 Spectral window and removal of prominent spectral features from the V-C2 Fourier transform. 282

Figure 9.20 Spectral window and removal of prominent spectral features from the C2-C1 Fourier transform. 283

Figure 9.21 Spectral scan for C2-C1 in the 0-20 c/d range. 284

Figure 9.22 Spectral scans (without window removal) for V-C1 and V-C2 in the frequency range 16-20 c/d. 286

Figure 9.23 Four frequency fit to the data for KW 207. 288

Figure 9.24 The residuals (observed-calculated) for the four frequency fit to the data for KW 207 shown in Figure 9.21. 289

Figure 9.25 The Fourier transform of the residuals of the 4 frequency fit to the KW 207 data. 290

Figure 9.26 Nonradial oscillations for different values of l and m. 297

Figure 9.27 Schematic representation of the infinite spectrum of frequencies of oscillation for different l values and p-modes. 300

Figure 9.28 Pulsation constants for HR 729 and KW 207 plotted against various modes predicted by Fitch's 2.0M43 grid. 302

Figure 10.1 Light curve for HD 32655 in the b filter from the night of Nov10/11-86. 313

Figure 10.2 Fourier transforms for HD 32655 for the nights: Nov 10/86, Jan 22/87, Jan23/87, Jan24/87 and Jan 25/87. 314

Figure 10.3 Light curve for HR 1971 in the b filter from the night of Nov 23/24-86. 317

Figure 10.4 Fourier transforms for HR 1971 for the nights Nov23/86, Feb2/87 and Feb20/87. 318

Part A

Personal Science and Its Implications for Science Education

(Chapters 1 - 7, describing the first part of this study, are an exploration of the idea of Personal Science and its relation to the nature of science, the astronomy that I do and the implications that Personal Science holds for Science Education.)

Chapter One
The Central Questions

1.1 Introduction

> *"Oh cool, its a kinda rainbow"*
>
> *Leah squinted as she moved the simple "cigar box" spectroscope back and forth to catch the light from the mercury vapour lamps visible from the living room window.*
>
> *"Remember to look off to the side - not straight through," I offered.*
>
> *"Now look carefully, what do you see?"*
>
> *"A rainbow, you know, roy-g-biv - just like in science."*
>
> *"Hum, let me look." I peered through the grating and sure enough the dominant lines of mercury vapour were there, somewhat smeared out but certainly not a continuous rainbow spectrum.*
>
> *"Leah, draw me a picture of what you see, exactly what you see..."*

The conversation with Leah went on for a number of minutes and evolved through several drawings of "exactly" what she saw. She had wanted to do her grade five science project on light and I had suggested that we make a simple transmission grating spectroscope which she would use to look at different kinds of light. That Leah persistently saw a rainbow and that I saw a bright line mercury vapour spectrum was intriguing and frustrating. This was supposed to have been a "classic" application of discovery learning. In the end we did reach a consensus but I was left with the nagging suspicion that it was reached only by a form of intellectual "coercion" on my part.

The story about Leah and the spectrum helps reveal one of the central themes of this thesis. Why would Leah see something that was not there? Did I really see what was there? Where did the notion of a continuous ("roy-g-biv") spectrum come from? How could our personal experiences of the same phenomenon be so different?

The episode with my ten year old daughter left me with the suspicion that school science(1) was at least in part responsible for this strange state of affairs. Leah saw a continuous spectrum because that is the only pattern of light she had ever seen (in her school text) with the name "spectrum" attached to it. This was a clear example of what Norwood Russel Hanson(2) described in his numerous writings on perception. Observation is rarely as simple as we think, it is always mediated by theory. In terms used by Abraham Maslow(3), Leah was relying on the **spectator knowledge** ("abstractness") supplied by her science instruction rather than the **experiential knowledge** ("suchness") provided by her senses.

A central idea to this thesis is that our present form of science education seriously undervalues the personal dimension of knowledge and fails to deal, in any significant way, with the role that non-rational, presuppositional and emotional factors play in science and in the learning of science. In the following chapters the role that these non-rational, presuppositional and emotional factors play in science will be explored and used to give flesh to the notion of "personal science". The argument will be presented that this notion of personal science is absent from our present science curricula and that the notion of personal science should become an active component of our thinking about science education. The examination of personal science and its function with respect to science and science education will be the primary goal of this study.

1.2 The Many Meanings of the Term 'Science'

It has long amazed me that, for some of my students, science remains remote and unappealing. Yet there are times when even the most jaded of students is enthralled, if only for the moment, by some idea or event that unfolds during the lesson. But such times are fleeting and do not last. Why should this be so? How can science, which has been at the focal plane of my interest for as long as I can remember, be apparently so unimportant to some students? This question becomes even more perplexing when

I consider the student whose interests seem to invite going "deeper". How can the student who is an avid photographer not be interested in the physics of light or lenses? Surely the keen musician would be interested in the science of sound. "Why are you so interested in fishing and hunting but not in biology?" Yet the invitation to see photography, or music or fishing in the science we do remains unanswered. "How is it possible that you can have no interest in science?" What can account for the apparent ambivalence towards science among some students? Such questions spring naturally from the day to day teaching of science.

As natural as these questions are, they are seriously limited in scope. At their root lies a failure to distinguish clearly between science and the portrayal of science. Hidden within the term science we find many layers: science as experienced by the scientist, school science as developed in textbooks and curricula, science as seen through the eyes of or experienced by the student or the teacher, science as it transforms and is itself transformed by technology and society.

In attempting to give flesh to the term "personal science" several ancillary questions will be addressed. One of these questions concerns the different meanings that appear to be attached to the word 'science'. During the past decade numerous studies(4,5) and commissions have called for the teaching of "real", or "authentic" science. What do these terms mean? As well, who or what informs curriculum planners when designing curricula that adequately represent science? Does the process movement(6) achieve an "authentic" or "real" portrayal of science? Does the strong Science-Technology-Society(7) thrust of the present day arrive at a truly desirable representation of science within the curriculum? Ultimately, we must face the question "Who speaks for science?" In considering this question, many voices may be heard speaking for science. In the study that follows I will explore several of these "voices" from the vantage point of the researcher as well as that of the educator and student.

1.3 Structure of this Study and Thesis

The present study draws upon my experiences as an astronomer and teacher engaged in a project which combines astronomical research with reflections on the teaching of science. While the astronomical research, on its own, is intended to lead to publication in an appropriate scientific journal, it will also provide a reflective base from which to examine the notion of personal science as well as permitting a criticism of some of the more common school science portrayals of science.

To reflect the dual nature of this study, and partly for reasons of clarity, the thesis has been divided into two sections. Section A, which consists of chapters 2 - 7, focuses on an investigation of personal science and its implications for science education. Section B, consisting of chapters 8 - 10, presents more technical discussions of the astronomical research carried out during the course of this study. Section B also serves as the backdrop against which the central questions of the thesis unfold and turns the discussion of personal science back onto what I do as both a scientist and science teacher. This will be accomplished in part through the use of narratives (Chapter 6) which arise from the doing of the astronomical research. An appendix summarizes publications that have arisen from this study.

1.4 Chapter by Chapter Summary of the Thesis

In recent science education discourse the term "authentic science" has arisen. The many layers of meaning that can be attached to the term "authentic science" will be explored in Chapter 2. In doing so the notion of personal science will be developed and form a theme that will be worked through the subsequent chapters of Part A of the thesis.

While it is tempting to reduce to a commonplace the student's personal engagement in the science being taught, Chapter 3 will show the depth and subtlety inherent in the notion of personal science. Indeed, the question of what constitutes a valid educational experience engaged no less a philosopher of education than John Dewey over half a century ago. Dewey strove to develop a theory of experience to illuminate the "organic connection between education and personal experience".(8)

Dewey's exploration of the educational experience grew within the context of the progressive movement in education of which he was a central figure. Much of what Dewey develops in Education and Experience is found (re-discovered?) within modern constructivist models of education (see Pope and Gilbert(9) or Osborne and Wittrock(10)). It will be argued in chapters 3 and 7 that Dewey's theory of experience and modern constructivist theories of science education find a natural anchor in the philosophical writing of Michael Polanyi and his notion of **personal knowledge**.

Chapter 4 will address the problem of communication of personal experience and will explore the use of narrative as a way of illuminating the personal dimension of science for the researcher as well as the student and teacher of science. It will be argued in this section that the narrative form is a powerful, and largely neglected, means through which the personal and many other dimensions of science may be communicated.

In Chapter 5 a semi-technical discussion of the astronomical part of the research will be developed and used as a context for chapter 6.

In Chapter 6 a series of personal anecdotes, arising from the astronomical portion of the study, will be used to reflect on personal science and its relation to science and science teaching. The astronomy project will provide a base from which to address the notion of personal science. What do I bring to my own research project? Can one, through reflection begin to uncover his or her own sense of personal science?

Chapter 7 will summarize Part A of the thesis. The epistemological underpinnings of traditional school science will be explored and contrasted with the ideas of personal science. A shift in the epistemology of science education will be suggested and the educational implications of personal science and its relation to constructivist models of education will be discussed.

Chapter 8 will discuss the ellipsoidal binary star system 42 Persei. UBV photometry will be presented for this system and used to construct a simple analytic model as well as a Wilson-Devinney computer solution for the system.

Chapter 9 will report on collaborative research on two delta scuti type variable stars. A tentative frequency identification and mode analysis will be offered for these stars.

Chapter 10 will present the research arising from a search for rapid variability in a group of peculiar A and F stars.

A brief epilogue will follow Chapter 10 and will consider the interaction of my being a scientist with that of my being a science teacher as well as suggesting future directions which this research may take.

1.5 Some Specific Educational Concerns of this Study

In developing the idea of personal science and its implications for science education a number of ancillary questions and concerns will be addressed.

One of the first questions to consider is why research in the sciences should be expected to lead to an increased understanding of the portrayal of science within curriculum. Research in the sciences can provide an experiential base from which to gauge the fidelity of a portrayal of science to the extent that a curriculum makes specific claims about the nature or methods of science. For example, a common portrayal of science invokes the "scientific method". Often this is cast in an inductive hypothesis-experiment-conclusion format. While it is clear that science has methods, is the hypothetico-deductive model what really takes place or is the hypothetical-deductive model a convenient rational reconstruction of science? This question is double-edged. While scientific research can lead to insight into the "doing" and "meaning" of science, this same research should be resisted as the only authority directing the portrayal of science within school curricula. Science, as it will be argued throughout the thesis, possesses a rich social dimension and, for purposes of integration within the entire school curriculum, must be presented to students in a context-laden form. As well, the doing of science is much different than the pedagogy of science education. This brings into focus the fact that a science curriculum must also address the needs of students, teachers, parents and community.

This point helps uncover the distinction that must be made between science and science education. Within the present study there exists a tension between the requirements of science on one hand and those of science teaching on the other. Any attempt to give meaning to the term "desirable portrayal" must work within this tension. A curriculum that is preoccupied with the rational and technical aspects of a science may, in fact leave out important non-rational, personal and social aspects of science. It may fail to "do justice" to the student. A curriculum that concentrates on the opposite pole of the tension may fail to do justice to the science. If, for the sake of classroom expediency or philosophical prejudice, a particular re-presentation of science is given, could the result lead to serious distortions when scrutinized from other points of view?

A related concern is the degree to which a project in astronomy is representative of science. The present research project in astronomy will be representative of science only to the extent that a shared framework exists between all sciences. This framework provides criteria for determining validity of research, conduct of scientists and communication of research. Unlike most other sciences, however, astronomy has a long and rich "amateur" tradition. Thousands of amateur astronomers world wide make valuable contributions to the science each year. This introduces a natural link in the study between the science of astronomy as understood and experienced by the professional and the science as experienced and understood by a "lay" group of non-professional scientists.

A final and practical concern for this study is whether it can lead to useful pedagogic insights having direct application to the teaching of science. The proposed research program should yield pedagogic insights in several ways. There is a direct personal pedagogic dimension to research. My own "evolution" as a researcher carries with it many potential insights into how a personal acquisition and assimilation of knowledge occurs. Part of this uncovers a sense of "question" that resides in research. It is the sense of "owning" a question that in a very personal way distinguishes the doing of science from merely "observing" science. Children have questions and many of them lead naturally to questions about science. What implications does attention to children's questions have for science teaching? Also, the reflections arising from this study will furnish an example of exploring one's personal science and how this can be communicated to others. The central thesis to be developed is that the personal dimension is an essential part of science and that science pedagogy should reflect this. This entails a changing direction for curriculum as well as providing some fundamental challenges to the epistemology of science education.

1.6 Limitations and Possible Strengths of the Study

In part A of the thesis the ideas of personal science will be developed. These ideas will emerge through both a synthesis of existing literature as well as personal reflections arising from my own research as an astronomer and teacher. An important limitation to recognize from the outset is the scope of the arguments to be presented. Part A of the study is concerned with what is viewed as a serious omission from science education - personal science as an active and vital component of our thinking about science education. The concept of personal science, in itself, is not sufficient to address the needs of science education. Rather, our understanding of science education should be augmented by our understanding of the personal dimension of science.

A second limitation arises from the personal nature of the reflections which grow out of the astronomical research component of this study. These reflections are not intended to serve as prescriptive statements about science. Instead they, more than anything, provide reflective situations from which to ask, critically, questions of science and science education. The reflections will be presented, initially, in the form of anecdotes, small vignettes of my research. The use of the anecdote as a methodological device has been addressed, at length, by van Manen(11,12). The validity of my findings will rest on the faithfulness of my representation of the ideas of others, the strength of arguments developed and the extent to which my personal anecdotes resonate with the experience of others.

The strength of this study resides in the rooting of the discussion of personal science within my own experiencing of science. While this could have been done as an empirical investigation of what other scientists say about their personal engagement with science, such a study would face the problem of disentangling an espoused view from a lived view. Mitroff(13) has provided an insightful study of just this problem.

In addition to addressing the notion of personal science, this study will also explore, in depth, the philosophy of Michael Polanyi and relate this to philosophical issues relevant to science education. Despite the numerous references to Polanyi which appear in the science education literature, there are very few detailed discussions of his philosophy.

Notes Chapter One

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3. Abraham Maslow (1966). The Psychology of Science. New York: Harper and Row.
4. Science Council of Canada (1984). Science for every student: Educating Canadians for tomorrow's world. Ottawa: Science Council of Canada.
5. National Commission on Excellence in Education (1983). The Nation at Risk. Washington: National Commission on Excellence in Education.
6. see, for example :NSTA. (1982).**Science-technology-society: Science Education for the 1980s**(National Science Teachers'Association Position Statement). Washington, DC:NSTA.
7. one articulation of the Science-Technology-Society idea is provided by the Science Council of Canada: Science Council of Canada. (1984). **Science for every student: Educating Canadians for tomorrow's world.**Ottawa:Science Council of Canada.
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10. Pope, M. and Gilbert, J. "Personal Experience and the Construction of Knowledge in Science." **Science Education 67(4),** 193-203, 1983.
11. Max van Manen (1984). "Practicing Phenomenological Writing". **Phenomenology + Pedagogy, vol 2, no.1**, 1984.
12. Max van Manen (1989). "By the Light of Anecdote". **Phenomenology + Pedagogy, vol. 7**, 1989.
13. Ian I. Mittrof (1974). The Subjective Side of Science. Amsterdam: Elsevier Scientific Publishing Company.

Chapter Two
Authentic Science - a Diversity of Meanings

2.1 Introduction

Science teachers are being challenged to present science as it "really is" rather than promote a mythic, textbook science. The call for developing scientific literacy or teaching real or authentic science appears in an increasing number of documents such as A Nation at Risk(1) along with the NSTA position statement(2) "Science-Technology-Society: Science Education for the 1980s". As early as 1975 Professor Thomas Symons(3), for example, charged that science in Canada was being taught as a body of knowledge and techniques without any mention of its personal, social or national relevance. In Report 36 of the Science Council of Canada(4) the presentation of an authentic view of science is listed among the eight priorities for changing the direction of science education in Canada. Due to the close parallel between the American and Canadian science curricula it is reasonable to expect that similar concerns hold for American science education. Understandably therefore, in both the NSTA and the Science Council of Canada documents, the view of what constitutes authentic science is embedded within the development of science-technology-society (STS) curricula.

While the development of an STS emphasis in science education is laudable, this in itself does not ensure the development of an authentic view of science. The principal intent of this chapter is to show that, while meaning in a phenomenological sense can be given to the term "authentic science", the term is so diffuse that considerable clarification is needed to allow it to function as a useful term for science educators. As well, the argument will be brought forth (and continued in subsequent chapters) that the notion of authentic science must necessarily embrace the personal dimension of knowledge.

In order for something to qualify as authentic, the Random House Dictionary suggests it must satisfy some commonly held denotations of the term "authentic." When applied to science these include, first of all, that the view is authentic in the sense of the Greek root **authentikos** if it arises from a primary or first hand experience of science. Science may also be considered authentic if it is in accord with a commonly held agreement over what constitutes science. Included could be agreement over methodologies, goals or meanings in science. Finally, a view of science may be considered to be authentic if it is a reliable or trustworthy or genuine representation of what science really is.

The first denotation suggests that only the originator of the science may have a claim to an authentic view. This of course dodges the question of where the science in fact emerges. Does it emerge directly from the researcher's lab or study, or does it develop through the articulation of teaching or does the science actually develop when grasped and fused with the student's personal experience? The second denotation presents us with the problem of in fact demonstrating that there is agreement over the methods or meanings of science. The third denotation raises the question of who is to decide what a genuine portrayal is. Does the researcher, the curriculum developer, the teacher or the student act as arbiter?

While the call for the development of an authentic portrayal of science is valid, giving meaning to the term "authentic" requires considerable clarification. In the present chapter the emphasis will be on the diversity or richness of meanings an authentic portrayal of science must encompass, including the meaning of authentic as it applies to the science student.

2.2 The Many Faces of Science

Report 36 of the Science Council of Canada suggests that a more authentic portrayal of science would include the history of science, science and technology and reflection on the nature of scientific knowledge. While these are all aspects of the phenomenon we would call "science", they by no means form a complete description. In what follows a more extensive list of attributes of science will be given. In addition to that, an important dimension of authenticity still to be explored is the interaction between the individual learner and the representation of science being offered.

2.2.1 Methodologic Fidelity

Science encompasses a large body of knowledge, principles and laws. As well, there are various techniques and methodologies, often employed in a fashion that is peculiar to a specific discipline. An authentic treatment of science must present this corpus in a faithful, factually sound manner. But how can one decide what constitutes an authentic portrayal of this aspect of science? Is there a common set of methods or understandings that, for instance, both physicists and paleontologists would recognize as "authentic" science?

Perhaps, it could be found in the process movement of the past decade. Perhaps the AAAS(5) sample of thirteen processes represents a distillation of the methods of science? Unfortunately, since the time of Bacon(6) no one has succeeded in arriving at a statement of scientific methodology that is universally acceptable. This does not mean that an approach like that of the process movement cannot have powerful pedagogic application but it does suggest that it is naive to equate the espoused practice of scientists with one authentic method of science. If the history of science is clear on any point it is in demonstrating the rich diversity of approaches that creative men and women have used in surmounting obstacles in science. Percy W. Bridgman's(7) terse: *"The scientific method, as far as it is a method, is nothing more than doing one's damndest with one's mind, no holds barred..."* may, if one seeks a simple definition of scientific method, be the best one can say.

2.2.2 Epistemological Considerations

Science extends beyond the methods just discussed. Ultimately, science cannot be divorced from the way in which people look at and make knowledge claims about their world. Science has at its core an epistemological dimension. A failure to bring this dimension to light in science teaching does not mean that students will operate without an epistemology. An excellent discussion of the role of epistemology in science teaching is given by Nadeau and Desautels(8) in "Epistemology and the Teaching of Science". In this paper the authors explore a number of the "scientistic" attitudes sometimes exhibited by students and teachers in the absence of a clearly articulated epistemology. They isolate five erroneous beliefs that are propagated in school science: "naive realism", "blissful empiricism", "credulous experimentalism", "excessive rationalism" and "blind idealism". In a similar vein, Popper(9) and later Gordon(10) reject the naive notion of the "bucket image" of the mind:

> our mind is a bucket which is originally empty, or more or less so, and into this bucket material enters through our senses...and accumulates and becomes digested...the important thesis of the bucket theory is that we learn most, if not all, of what we do learn through the entry of experience into sense openings; so that all experience consists of information received through our senses...

Such a view is implicit in the inductivist-empiricist tradition found in many portrayals of science. Indeed, a recently completed study by Aikenhead(11) et al of the attitudes and understandings of Canadian students regarding the nature of scientific knowledge reveals that most operate from an inductivist-empiricist position. The authors conclude:

> the data provide clear support for the Science Council of Canada (1984) recommending a renewal of science education toward teaching authentic science...

On what would an authentic view of the epistemology of science be grounded? Could we turn to the philosophy of science for an answer? Over the past decade numerous authors have called for increased attention to the philosophy of science as it applies to science education (see Smolicz(12) and Nunan or Hodson(13) for more comprehensive treatments). Again, we face the problem of deciding whose philosophy of science to adopt. Do we take the presuppositionalist position or the falsificationist or the hedonist position? Each of these and others have been applied to science education and each has found both adherents and critics among science education theorists. To pursue the point further, consider in more detail some of the more influential philosophic positions:

i. The Presuppositionalists

Prominent among this group are both Michael Polanyi(14) and Thomas Kuhn(15). In Polanyi's work the notion of tacit knowledge is developed. In this respect, the experiential level of science is seen as an essential aspect of the education of the scientist in ways that cannot be completely articulated. The scientist acquires a deep and tacit understanding of his or her science through "close personal association with the intimate views and practice of a distinguished master." In light of Polanyi's philosophy, the process movement faces a significant challenge, as do any highly content oriented curricula. A dominant theme in the presuppositionalist philosophy is the role that personal belief and commitment play in science.

Similarly, Kuhn's central theme of paradigm development and maintenance points to the sense of inculcation of the scientist through factors that are not completely rational or articulated. This introduces a sociological dimension to the philosophy of science that is often overlooked in science curricula. In either case, the number of science education papers that have cited the ideas of both Polanyi and Kuhn in the past two decades indicate that they have had some impact on science education.

ii. The Falsificationists

The most influential proponent of this position is Sir Karl Popper(16). Popper vigorously denies the presuppositionalist notion of belief in science. Paraphrasing the words of E.M. Forster, Popper writes: "I do not believe in belief." Popper resists the subjectivity of the presuppositionalists and instead suggests that scientific theories be built around the doctrine of falsifiability. Coupled with this idea is Popper's thesis of the third world of objective knowledge in which the products of science, its theories and constructs, are seen as independent of the knower and exist in an objective sense. Science curricula built around Popperian ideas would accentuate far different things than would a presuppositionalist curriculum. Derkse(17) and Akeroyd(18), for example, have shown that laboratory experiments which are either explicitly or implicitly falsificationistic in purpose have the pedagogical effect of allowing students to participate in the formulation (and delimitation) of various scientific generalizations.

Again, one merely needs to look at the large number of papers in the literature that cite Popper's ideas to conclude that the falsificationist position is well represented among educational theorists.

iii. The Hedonists

Both the falsificationist as well as the presuppositionalist positions, and especially that of Kuhn, are vehemently attacked by P.K. Feyerabend(19). Feyerabend charges that Kuhn's position confuses the "is-ought" problem of the nature of science. Does Kuhn describe how science is or how it ought to be? In this lies an important question for educators attempting to portray science in an authentic fashion. In Feyerabend's opinion, the presuppositionalist ambiguity on this point results in an aimless view of science and as such seriously weakens its value to science education. Feyerabend charges that if Popper was taken seriously, then most - if not all - scientific theories will be found to have been falsified at least once and hence would have to be rejected. In fact, Feyerabend rejects the very notion that a prescriptive rule or set of rules can be found to decide the truth of a scientific theory. To counter this problem Feyerabend advocates a position that encourages the proliferation of ideas - a 'follow your own inclinations' approach that he calls personal hedonism.

We have only considered three philosophies of science but already it is apparent that there is considerable divergence among them. Further, the question of portraying science as it "is" or as it "ought" to be becomes a crucial question in deciding if an authentic representation is viable. It is doubtful that philosophy of science will provide us with an authentic epistemology of science.

2.2.3 Personal Science

An aspect of science that is often overlooked (if not openly denied) is the personal dimension of science. Scientists, just as students, are complex and motivated by a host of factors. What a scientist espouses and what he or she in fact does can often times be quite different. Ian Mitroff(20) provides a fascinating glimpse of the personal dimension of science in The Subjective Side of Science. Mitroff found that while the scientists entrusted with the analysis of the Apollo moon rocks asserted the fundamental priority of "facts over theory" they were often highly resistant to dropping favored theories in light of conflicting evidence. Scientists often work in highly individual and idiosyncratic ways. Gerald Holton(21) illustrates the phenomenon of personal science in the following way:

> He (the scientist) proceeds through his problem like an explorer through a jungle, sensitive to every clue with every faculty of his being. Indeed, some of the greatest theoretical scientists have stated that during those early stages of their work they do not even think in terms of conventional communicable symbols and words.

One of the central tenets of the notion of personal science is that the naive-objectivist conception of the relationship of the scientist to his or her science is faulty. Michael Polanyi makes this point very clearly in Personal Knowledge. In Polanyi's analysis the ideal of scientific objectivity, independent of the passion and engagement of the scientist is a "delusion and in fact a false ideal". Polanyi's thesis has important implications for the teaching of science for it develops the idea that a great deal of what constitutes science, its methods, judgments, passions can only be acquired through a personal involvement of the student with that science:

> Connoisseurship, like skill, can only be communicated by example, not by precept. To become an expert wine-taster, ... or to be trained as a medical diagnostician, you must go through a long course of experience under the guidance of a master. Unless a doctor can recognize certain symptoms, eg. the accentuation of the second sound of the pulmonary artery, there is no use in his reading the description of syndromes of which this syndrome forms part. He must personally know that symptom and he can learn this only by repeatedly being given cases of ausculation ...

If we are to portray science authentically then the lived experience of science must be attended to. This, however introduces the question-whose lived experience?

2.2.4 Private Science

Much, perhaps most of what a scientist does never leaves the confines of the lab or study. This is the realm of private science and exists as an intermediate form between the individual, partly tacit personal science and the published, highly scrutinized public science. In the textbook dominated presentation of science, students rarely, if ever, encounter this aspect of science. Instead, students often acquire an almost production-line image(22) of science. The reality of doing science is one fraught with blind alleys and false starts. Private science is both arduous and exhilarating. It is in this realm that the elements of personal judgment and experience are transformed into the first faltering steps that may later emerge as a published bit of knowledge (public science). It is also in this realm that conscious moral and ethical decisions are made.

There is also a dark side to private science. Although we can look to Archimedes or Galileo as examples of "scientists for hire", twentieth century science is becoming increasingly industrialized(23). The pressures of industrial competition or military advantage are creating a new private science which, by design, is hidden from public scrutiny. If we are serious about our call to give students an "authentic" view of science then at some point in their education students must encounter the private side of science.

2.2.5 Public Science

Personal science must eventually be transformed into public science. In Thomas Kuhn's conception of science, the principal role of the paradigm is to regulate and shape the formal statements (research papers to textbooks) of the science. As such, public science is a very real part of science. But it also "covers its tracks" well. Public science only rarely reveals where it came from (its personal and private origins). By its very nature, public science is visible to students-inasmuch as any textbook is a public statement. In developing an authentic view of science, however, it will be vital that students grasp the position of public science within the entire phenomenon of science. Can we arrive at an understanding of public science that we could claim as authentic?

i. Popper's Third World of Objective Knowledge

Perhaps we can use Popper's conception of objective knowledge(24) to form an authentic understanding of public science. In this case we could identify public science with what Popper calls the "third world" of knowledge. Popper originally introduced his third world hypothesis to combat what he saw as an increasingly subjectivistic tendency in science. This led Popper to assert that there exists a sense of knowing that is independent of anybody's claim to know or believe. It is "knowledge without a knowing subject". Such knowledge would exist in the form of theories, arguments, conjectures as well as books and journals and would be independent of the subjective (second world) knowledge that characterizes our dispositions to behave or react and the world of physical objects (first world). When we say, for example that we understand Einstein's thoughts on mass-energy we are, according to Popper, asserting (a second world statement) that we have an understanding of something that is completely objective and outside ourselves - the mass-energy relation. Nor does it matter whether or not our assertion (that we understand) is correct, it is the fact that the potential of understanding the mass-energy relation exists that anchors it in the third world. According to Popper then, we can disentangle an objective knowing from a subjective asserting or believing or knowing. Thus, if we agree with Popper, it may be possible to arrive at a genuine portrayal of public science through this third world of objective knowledge (for an example of Popper's third world notion applied to science education see Hodgson(25)).

ii. Arguments Against Popper's Third World Hypothesis

To persuade his readers Popper offers the following thought experiments:

> Experiment(1). All our machines and tools are destroyed, and all our subjective learning, including our subjective knowledge of machines and tools, and how to use them. But libraries and our capacity to learn from them survive. Clearly, after much suffering, our world may get going again.
>
> Experiment(2). As before, machines and tools are destroyed, and our subjective learning, including our subjective knowledge of machines and tools, and how to use them. But this time, all libraries are destroyed also, so that our capacity to learn from books becomes useless... in the second case there will be no re-emergence of civilization for many millennia.

How compelling is the (implicit) suggestion in the first experiment that "recovery" will occur solely because the libraries and books (the third world) exist along with our capacity to learn? A point not raised is how long and by what means this recovery will take place In the first place, recovery would occur only within the context of how the people of the experiment perceive the problems at hand. That the problems exist in an objective sense is not the issue, rather it is the subjective recognition of what constitutes a significant problem. Secondly, people rarely solve significant problems in isolation. The very fact that there is a public science indicates the importance of communication between scientists. This weakens rather than strengthens Popper's point, however. Consider the importance that informal and formal communication plays in the development of a science. In the early stages of the science discussions are far ranging and often foundational (consider the Bohr-Einstein debates). This is still part of public science but it can hardly be maintained that it is purely objective.

Ultimately, Popper's third world doctrine rests on a particular way of structuring the notion of objectivity. Michael Polanyi, on the other hand, does not deny the existence of objectivity - it forms an important part of what he says about science - but he does reject the disjunction between subjectivity and objectivity.

> Yet the prevailing conception of science, based on the disjunction of subjectivity and objectivity, seeks - and must seek at all costs - to eliminate from science such passionate, personal, human appraisals of theories, or at least to minimize their function...

We shall find Personal Knowledge manifested in the appreciation of probability and of order in the exact sciences, and see it at work even more extensively in the way the descriptive sciences rely on skills and connoisseurship. At all these points the act of knowing includes an appraisal; and this personal coefficient, which shapes all factual knowledge, bridges in doing so the disjunction between subjectivity and objectivity. It implies the claim that man can transcend his own subjectivity by striving passionately to fulfill his personal obligations to universal standards(26).

Polanyi's idea of objectivity is rooted in the individual. Popper's idea of objectivity is independent and autonomous of any individual. The decision of which view is correct, it would seem, is a matter of preference. It should be clear however that either of these positions, though poles apart, can be used to develop a notion of public science and thereby calls into question the meaning of authentic public science.

2.2.6 Historical Science

Science is, undeniably, part of our cultural heritage. To attempt to teach science without developing the important historical place of science within our culture would give a seriously distorted view of science. Indeed, attention to historical science must go beyond the didactic (history as a motivator) and extend to the history of ideas themselves. Brouwer(27) and Singh give a useful example of how historical insights can help reveal the "tentative nature of scientific knowledge". It can also provide plausible ways of introducing some of the other dimensions of science. For example, a discussion of the Newton-Huygens debate does more than underscore the nature of light. It also shows students that very different explanations can often "fit the same facts" as well as showing that what one collects as "fact" is often related to what one believes (the fuzziness of images formed when light passed through a small opening was of no importance to Newton but was clear evidence of wave behavior for Thomas Young a century later). The history of science can also illustrate what Gerald Holton(28) calls the **themata** of science. These are broad themes (to be explored in greater detail in the next chapter) that, according to Holton, form the presuppositional base of science. Modern day particle physicists may be working out the theme of discreteness (as opposed to continuity) that is, in essence, the same theme that motivated the Epicureans. This same theme may be at work in molecular biology (the atomic nature of genetic information) or artificial intelligence research (the atomicity of thoughts). One can envision applying a thematic analysis to a topic in science much as one applies such an analysis in other academic disciplines. Themata stretch across disciplines as well as back in time and can help reveal (when warranted) a degree of uniformity between seemingly unrelated fields.

2.2.7 Societal Science

Science is embedded within a broader societal matrix. As such it is shaped and in turn helps shape the values of society. Any portrayal of science that ignores the societal values of science is incomplete. Aikenhead(29) addresses this point and develops the idea that science holds both constitutive and contextual values. Constitutive values comprise those attitudes and tendencies which make up the scientist's view of a discipline. Contextual values accrue from ethical, economic, religious, ideological and cultural values. These provide a societal context to science. It is primarily in the ambiguous areas that contextual values "seep" into a scientist's value structure. When scientific information is inconclusive, contextual values become increasingly important. One needs only reflect briefly on the structure of most science curricula to see that little room is set aside for dealing with inconclusive topics. A discussion of redox reactions would not invite the use of contextual values. An application of the same concepts to the topics of acid rain or toxic waste disposal would bring in contextual values as well as requiring the presence of constitutive values. The tying together of basic science and societal issues will require significant restructuring of most science curricula. In a recent series of articles Aikenhead, Fleming and Ryan(30,31,32,33) present a detailed picture of the views of Canadian high school students regarding the interaction between science, society and technology. One hopes that studies such as these will provide the insight needed to improve the way in which the societal dimension of science is developed in the classroom.

2.2.8 Technological Science

Science and technology, working in tandem, exert a profound shaping influence on humanity. Much of present day science is intricately interwoven with the workings of technology. Mass spectrometry, superconductors, the proposed SuperCollider or the Hubble space telescope are possible because of highly refined technologies. In turn, science feeds technological innovation. It is the contention of Donald George(34), writing in "An Engineer's View of Science Education", that science education reform, after sputnik, placed undue emphasis on the theoretical aspects of science. This was at the expense of a more practical, technological science. George cites the decline in secondary and post secondary science enrollments as support for his claim. Even if one does not fully accept George's analysis of the decline in enrollments, his call for a more balanced development of science and technology within science education still stands.

Another issue of concern is the understanding, on the part of students of the respective roles of science and technology in society. The study of Aikenhead et al reveals considerable blurring occurs in the minds of (Canadian) students regarding the distinction between science and technology. In an authentic treatment of science distinctions between the roles of pure research, applied research, technological research and development need to be made.

2.2.9 The Aims of Science

If we are to offer an authentic view of science then, at some point we must introduce a position regarding the fundamental aims of science. In doing so we will discover a deep rift. On the one hand we will encounter those who maintain that science can only be done under the banner "Knowledge for knowledge's sake". On the other is the position that science must, ultimately contribute to the well being of humanity, to ease suffering and hardship. Nicholas Maxwell(35), writing in From Knowledge to

Wisdom, calls for a radical re-direction of the aims of science. It is his contention that science, for the most part is represented by the first position but must, in light of the global crises upon us, align itself with the second position.

A question also arises over whose agenda is being met in science and science education. The aims that one presents for science rest, in a large measure, on the answer given to the question: Who pays for science? Science can no longer be viewed as an independent entity that serves to enlarge humanity's understanding of nature. Today science must be understood in the light of private, public, industrial or military agendas. This also helps draw into relief the necessity of considering whose agenda is being met in the portrayal of science. There is, for example, growing consensus that one of the most important areas of science education reform must be the Science-Technology-Society (STS) interaction. What agendas drive this specific curricular reform? There are strong pedagogic reasons for moving science curricula in this direction but there are also clear industrial and nationalistic agendas that call for the development of STS curricula. Again we see that agreeing upon an authentic aim for science becomes problematic. Those aspects of science that emerge from a specific agenda could, conceivably, induce a skewed portrayal of science.

Nine aspects of what would comprise "authentic" science have been given. These aspects are by no means an exhaustive list but they do help underscore the rich diversity of science as well as the immense difficulties that exist in attempting to define authentic science. To arrive at the goal of authentic science, science education must attend to meta-scientific and extra-scientific aspects in addition to the more traditional theoretical side of science. As we have seen, arriving at a consensus on any one of these aspects seems unlikely. Instead, we are constantly faced with a plurality of positions that are at work in the cultural phenomenon we call science.

2.3 Layers of Experience

It may seem banal to state it, but education involves being with, working with, teaching and learning from children. This means that our notion of authenticity must be mediated by the realization that what is authentic for the adult may not be authentic for the child and vice versa. Any attempt to develop an authentic view must first be grounded in the individual. In this respect the quest for a more authentic portrayal of science must come to grips with the personal dimension of knowing and entails a shift in the epistemology of science education. We cannot maintain that an authentic view of science is strictly a matter of curricular reform. As Marcia Linn(36) puts it:

> There is growing consensus among researchers from psychology, anthropology, philosophy, education and other disciplines that learners construct a view of themselves, just as they construct beliefs about natural phenomena.

With this in mind, what does it mean to have a child acquire an authentic view of science? What does it mean for a high school student or a college freshman to have an authentic view of science?

Science, at its most elemental level is a way of giving meaning and structure to our world. Whether it be a scientist grappling with General Relativity theory or the Grand Unified Theories of physics, or the child wondering why bread rises, each is trying to make sense of his or her own world. To ignore the fact that children are busily constructing their own views of the natural world is to invite failure in having students develop what we, as educators may consider to be an authentic view of science. If we are to take seriously the challenge of teaching a more authentic view of science we must first be willing to lay aside the adult-centered or teacher-centered perception of authentic science. We must move beyond the situation David Stenhouse(37) describes:

> "Most publications on the 'children's/teacher's science distinction, however, tend to see "children's science" as merely provisional - and

> probably - erroneous, as something to be taken account of in order to be corrected.

This invites, however, a seeming paradox; we come to our students as we are, with an adult perception of science. How can we teach our students and yet honor their own perceptions? Some clues on how to escape this conundrum are given by Munby(38) and Fensham(39). Munby has addressed the need to work with students' ideas to avoid what he calls the state of "intellectual dependence" that characterizes the relationship between many students and teachers. Fensham has suggested new objectives for science curricula rooted in the belief that students' ideas and world views play a crucial role in science education. Evidence is mounting (White and Tisher(40)) to show that the repeated lack of success encountered by teachers when attempting to change student perceptions stems from, in large measure, a failure to recognize the student's pre-existent framework. Indeed, students' resistance to change is surprisingly like scientists' resistance to change (Barber(41), Mitroff(42))!

The presence of a small number of fairly consistent naturalistic explanations which differ from one another has led to the term alternative conceptions (Gilbert, Osborne and Fensham(43)) when describing children's ideas. Terms such as children's science and preconception have implicit in their meaning the direct personal experience interpretation of authenticity, i.e. if the child believes his or her explanation to be an adequate explanation of the experienced events, it is authentic for him or her. On the other hand, the use of the term "misconception" is an implicit assessment of that explanation in its relation to what is accepted as correct or authentic by a relevant community (teachers, parents, scientists etc.). The prefix "mis" implies a negative valuing of the child's view as in some sense lacking authenticity.

However these ideas are labeled, their resistance to modification through school science has been widely documented (Whitrock(44)). There is no strong reason to suppose that primarily verbal methods of instruction would have significant impact on ideas authenticated in personal experience and the reliability of interpretation of that experience. This point will be addressed in greater detail in chapter four.

Since authenticity is inextricably bound up in the learner, it is a highly problematic educational concept. This does not mean that "authenticity" does not exist within the context of science education. Like motherhood, however, saying that it exists and saying what it is are two very different things. Unless thoughtful attention is given to the richness implicit in an authentic portrayal of science, the phrase authentic science runs the danger of becoming just another buzzword of science education.

2.4 An asymptotic approach to authentic science

In attempting to give meaning to the term "authentic", science educators should deal with the rich diversity of meanings of the term authentic. Each of the aspects of science discussed previously contribute to the development of an authentic portrayal of science. As well, at different stages in a student's education it may be pedagogically wise to emphasize different facets of science. Rather than attempting to establish an authentic portrayal of science at a specific point in the student's education it may be more useful to see authenticity as an asymptotic state towards which the curriculum is pointing.

While it is difficult to identify an "authentic" view of science, the rich diversity of meanings inherent in the term authentic science could be used to identify those cases where a portrayal of science is unauthentic. Any portrayal of science that either omits important dimensions of science or applies inappropriate dimensions (with respect to the student) could be called unauthentic. A science education that is tending towards authenticity would be one that draws in as many relevant aspects of science as are appropriate at a given point in the student's life. For the young student this may mean no more than allowing him or her the opportunity to explore the personal dimension of science and may imply that greater emphasis be placed on the development of an experiential basis rather than in the formal development of "scientific facts and ideas".

For example, when an elementary student studies light, instilling a sense of wonder or curiosity may be of much more benefit (and more authentic) to that student than in carefully drawing out the adult perception of light as an abstracted notion. This keeps before us the question of what it means for something to be authentic for the student at a particular point in his or her intellectual development. As teachers, we would be wise to curtail our propensity to explain refraction, for instance, and instead concentrate on providing the student with many different situations in which to develop a personal (tacit level) understanding of the phenomenon. As that student matures the personal aspect of science will reach out to draw connections to other dimensions of science. For the older student (junior high school) this would lead to the idea of theorizing and experimentation. Still later, perhaps in high school, historical and social-technological dimensions of the phenomenon could be introduced. All along the way, the teacher would face the peculiarly pedagogic question: What is appropriate for this child, now? Rather than attempt to achieve, at a specific point in our curriculum, a situation of "authentic portrayal", we should see that by attending to the richness inherent in science, the student is led towards a more authentic view of science.

In the following chapter the notion of personal science will be explored in greater depth and developed with respect to Holton's thematic analysis of science and Michael Polanyi's epistemology of personal knowledge. In later chapters emphasis will be placed on the communication of one's personal science with others and the active role that such communication can play in the teaching of science.

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Chapter Three
Personal Science

3.1 Introduction

> *"Just what kind of shell are we talking about, is it optically thick or thin, does it bulge toward the center or what?"*
>
> *The question concealed a note of impatience. It was the fourth session of the morning and participants of the International Astronomical Union Colloquium on Algol Systems were becoming restless. It was the third day of talks, the August sun had just broken through a gray and drizzly Victoria sky for the first time in a week and I, for one, was looking forward to going for a walk. The morning session had been heavy and the hundred or so participants were starting to show signs of wear.*
>
> *"Really, we must come to some agreement on something so basic."*
>
> *The questioner continued in his thick eastern European accent;*
>
> *"All I want to know is what's the "Party Line?"*
>
> *"Joe, relax we are in the west now!"*
>
> *The interjection from the distinguished eastern block scientist sitting in the front row was greeted with spontaneous laughter from all corners. The tension was broken and the question period continued.*

Science, like all other human activities involves people, individuals with histories, philosophies, attitudes and beliefs. Looking about the room at the International Astronomical Union Colloquium on Algol systems(1) I saw one hundred or so astronomers from twenty-one countries meeting together for a week in Victoria to discuss common research problems. After a few days I began to recognize the individual styles in many of these people. Some were extroverts - willing to jump in at any point and debate. Others had a dry wit and some seemed to have no humour at all! It soon became clear that the participants were easily as fascinating as the stars they were discussing.

The call for the "party line" was the attempt of one of the astronomers to delineate the boundaries of the public dimension of what we were all grappling with. It was an appeal to the consensual or paradigmatic aspect of scientific discourse. Science has an unmistakably public dimension and the end goal of any scientific meeting such as this is to consolidate this knowledge into a coherent, unified whole. What eventually appears in the form of research papers or pages in a science text is this "public distillation" of ideas. From the "outside" then, science can appear very unified and tidy - something similar to Popper's ideal of third world knowledge discussed briefly in the last chapter. From the "inside" however, science appears in a much different light. From the vantage point of the participant science unfolds in a context of human imagination, struggle, despair - the whole panoply of human attributes. In this I differ sharply from Popper's notion of a third world of objective, contextless scientific knowledge. The anecdote used to begin this chapter attests to the interplay between the individual and the shaping of public knowledge. As the history of science clearly shows, the public character of science can at times be dominated or significantly modulated by individuals. Science is more than just the facts, the formulae or the great law structures that (apparently) describe the universe. Yet what do we impart in our science lessons? Do our school portrayals of science or teaching methodologies reflect any more than the public dimension of science? Is there any place for the sense of wonder (or despair) that animates the scientist? Do our texts ever convey to students science in its richness? In this chapter I hope to explore the human and contextual dimension of personal science and in so doing examine some of the essential aspects of Michael Polanyi's philosophy of personal knowledge. The implications that the notion of personal science has for science teaching will be explored in the chapters which follow.

3.2 Holton's Thematic Analysis of Science

One persistent characteristic of science is controversy. At any time, in any area of current scientific research there exist competing and often contradictory theories, models or interpretations. Are the red shifts of galaxies cosmological in origin (ie, related to recessional velocity) or due to as yet unknown and hence possibly local phenomena? Where is the missing mass in the universe(2) - is it found in dark stars (brown dwarfs(3)), black holes or heavy particles left over from the big bang? Do black holes even exist? Do "mini-comets(4)" punch holes in the Earth's upper atmosphere at a continuous rate? As old controversies are resolved new ones arise and so science goes.

The origin of these controversies provides a valuable insight into the nature of science and helps to reveal that beneath the surface of seemingly new ideas and controversies lie some very old and common themes. As Gerald Holton(5) contends, scientific research and discourse is carried out against a backdrop of persistent and often very ancient notions, presuppositions or judgments that can be encapsulated within the term **themata**. Holton's introduction of the thematic dimension of science suggests significant implications for science education.

According to Holton, modern scientific discourse contains two rather distinct types of statements. There are empirically oriented statements about the phenomena at hand. These shall be called **phenomenic** propositions and are ultimately reducible to meter readings. Another kind of statement arises from the composition of meaningful analytical, mathematical statements within an accepted axiomatic system. Such statements are termed **analytic** propositions. Within the current traditions of logical positivism and its variants, any meaningful scientific statement is ultimately reducible to statements of either a phenomenic or analytic nature. Figure 3.1 helps illustrate this idea by suggesting that the phenomenic and analytic aspects of statements can be viewed as orthogonal to each other and together they establish a plane in **proposition space**. Any scientific statement contains to varying measure both phenomenic and analytic components and can be placed accordingly within this proposition space. In a purely schematic sense then, scientific concepts and ideas can be viewed as clusters of statements contained within the two-dimensional phenomenic-analytic continuum.

Such a two-dimensional view of science has had a pervasive influence in science education. In its more blatant form it appears within the rubric of behavioral models of education. Statements of objectives can be seen as protocol statements that find their anchor in the phenomenic-analytic continuum. The process movement, for example, although more subtle than earlier behavioral objective models, sought to elicit the things that scientists do (classify, infer, deduce, etc) with the goal of having students emulate such behaviors. The hypothetico-deductive model of science is another example of a widely used model of science that focuses on the phenomenic-analytic plane of discourse. The generation of hypotheses, experimental testing and subsequent re-evaluation of ideas can, according to the two-dimensional view, be completely specified as a set of phenomenic and analytic protocols.

Such a concentration on the phenomenic-analytic plane carries with it an implicit bias that focuses attention on the public dimension of science with a resulting diminution and possible exclusion of some of the other dimensions of science considered in the previous chapter. Holton argues that, since the seventeenth century, formal scientific discourse appears to have been confined to the phenomenic-analytic plane. Indeed, as

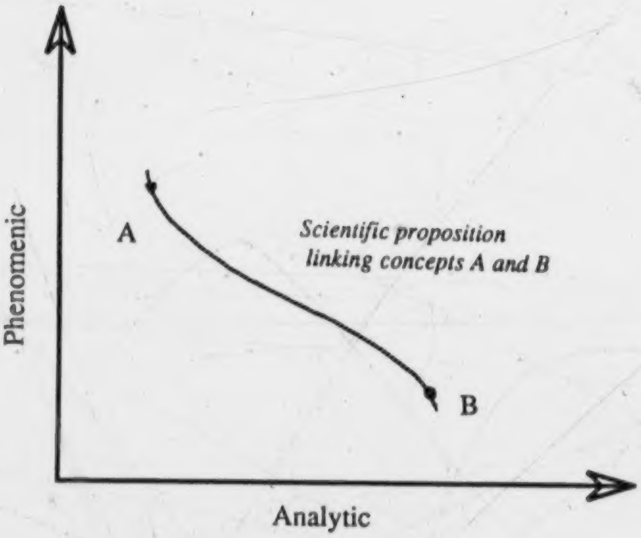
Phenomenic
A
Scientific proposition linking concepts A and B
B
Analytic

Figure 3.1 Holton's proposition space in which scientific ideas are considered to have a two-dimensional nature. The empirical content of an idea is indicated by its position along the phenomenic (vertical) axis. The analytic content of the idea is indicated by its placement along the analytic (horizontal) axis. Propositions are line segments in this two-dimensional space.

Holton suggests

> A good argument can be made that the silent but general agreement to keep the discourse consciously in the phenomenic-analytic plane where statements can be shared and publicly verified or falsified is a main reason why science has been able to grow so rapidly in modern times. The same approach also characterizes the way science is taught in most classrooms and is "rationalized" in most of the current pistemological discussions.(6)

There are, however, compelling reasons to suspect that scientific statements are not uniquely specified by their placement on the phenomenic-analytic plane.

Consider the problem of deciding what counts as an observation in science. Selection criteria - either sensory or instrumental - must prefigure any observation. My choice of instrument(7) (a photomultiplier tube and pulse counting electronics) has already imposed a selection on the observations I will accept. A cell biologist looking through a microscope will ignore the chromatic aberration of the lenses or specks of dust degrading the image and record what his or her experience suggests is worth noting. The sheer number of sensations imposes the need for selection criteria. Yet another problem of observation concerns those events which appear to be non-repeatable and hence not malleable to the techniques of science. An example would be reports of "stones falling from the sky" - ignored during the seventeenth century but later recognized to be meteorites. Still other examples would be the often reported sound accompanying bright aurora or the cosmic "flashers(8)" reported by a number of North American amateur astronomers in the mid 1980's. How does one decide when to discount an observation and when to consider it as a true "phenomenon"?

Still another problem of deciding what is a legitimate phenomenon focuses on the place of anomaly in science. An example of considerable current interest is found in the red shift controversy. Are quasars as distant as a cosmological interpretation of their redshifts would suggest? Halton Arp(9), a distinguished observer of galaxies and quasars, has compiled a considerable list of peculiar associations between quasars and normal galaxies. Such associations, Arp posits, show a clear physical connection between the objects. Since a normal galaxy has a much smaller redshift than a quasar it should be much closer to us than the highly redshifted quasar. Arp's observations as well as his conclusions have been roundly and vigorously criticized. Part of the criticism (although not all) is that Arp's observations are anomalies or chance alignments of unrelated galaxies and hence not "true" phenomena. Statistical methods may be employed to test this suggestion. Both the adherents and critics of Arp's views have carried out such tests and argue that statistics support their contradictory claims! The choice of when to accept that an observation is of a "true" phenomenon and when to dismiss that observation is one that requires expert skill. The scientist must decide what clues to follow and which ones to ignore. In trying to uncover the criteria used to do this we will be forced out of the phenomenic-analytic plane of conventional scientific discourse.

Similar problems occur when one considers what is a valid analytic system to adopt. Prior to the development of non-Euclidean geometries, and during the height of the Newtonian-Cartesian world view, there was little problem in determining what was the correct analytic system to use. It was the mathematical machinery built around Euclidean geometry and calculus coupled with Newtonian mechanics. With the advent of quantum theory, relativity and in recent years chaotic systems theory the situation has changed decisively. It is now realized that Newton's theory of gravitation is not complete - there is phenomenic support to this conclusion. In its place general relativity (and several other theories) has been erected. According to most physicists gravitational forces are evidence of a curved (non-Euclidean) spacetime(10) continuum. Gravitation can, however, be described in a flat (Euclidean) spacetime if one is willing to give up the parsimony and elegance of the curved spacetime analysis. Different, and possibly contradictory analytic systems may be employed in science.

The criteria on which to base the choice of which analytic system to adopt again forces us out of the phenomenic-analytic plane.

Finally, consider one of the most characteristic traits of science alluded to earlier in this chapter - controversy. Even if scientists appear to have adopted similar phenomenic and analytic systems, controversy still occurs. How does one understand how groups of equally competent scientists can use the same methods of analysis and phenomena and yet reach different conclusions? Examples of this abound in the history of science. Two examples from 20th century astronomy are the "great debate" between Harlow Shapley and Heber Curtis(11) concerning the size of the galaxy and between A.S. Eddington and S. Chandrasekhar over the structure of white dwarf stars. The Shapley-Curtis debate centered around Shapley's suggestion that the Milky Way Galaxy was much larger than suspected during the early part of the century. In Shapley's revision, the Galaxy grew from 30 000 light years in diameter to about 300 000 light years across. At the same time the Sun was no longer viewed as being near the center of the Galaxy, instead it was placed roughly 65 000 light years away from the galactic center. The debate was eventually resolved, for the most part, in Shapley's favour. What is of interest, however, is the state of polarization that prevailed among astronomers for the decade or so predating and following the debate and how apparently equally competent atronomers, using the same data and techniques, could arrive at such significantly different conclusions.

The Eddington-Chandrasekhar controversy is also of considerable interest. In the 1930's Eddington was the pre-eminent authority on stellar structure and laid much of the groundwork for Chandrasekhar's remarkable suggestion that stars of a sufficiently large mass -once their nuclear fuel was spent- would collapse without stopping. Eddington described this as "stellar buffoonery" and though he understood Chandrasekhar's theory very well he felt that "there should be a law of nature to prevent a star from behaving in this absurd way"(12). Today the existence and behaviour of white dwarf and neutron stars and the notion of uncontrolled collapse to a black hole is relatively uncontroversial and stands secure within the theory of stellar evolution(13). What accounts for Eddington's tenacious resistance to the ideas put forth by Chandrasekhar?

If our aim is to come to a more complete understanding of science and to ultimately reflect this in our school portrayals and teaching methodologies, we have no choice but to leave the phenomenic-analytic plane of conventional scholarship and consider what Holton calls the "thematic dimension" of science. In addition to the phenomenic and analytic axes of the phenomenic-analytic plane, we require a third dimension - the thematic dimension. Along this dimension we find the fundamental presuppositions and beliefs held by scientists. We encounter part of what we have come to identify as the **personal** dimension of science. Within this dimension we encounter the themata of science - ideas which apparently derive neither directly from, nor resolve into, observation or analysis. The resulting three dimensional proposition space is shown in Figure 3.2 where ideas are now seen to possess phenomenic, analytic and thematic components.

Through thematic analysis the nature of scientific controversy is cast in a new light. In Holton's words, it helps answer the question:

> If sound discourse is directed entirely by the dictates of logic and empirical findings, why is science not one great totalitarian engine, taking everyone relentlessly to the same goal?(14).

An example used by Holton to explain the existence of controversy is the idea of force. Holton writes that at the thematic root of the notion of force, lies the "principle of potency". This is an old, seemingly universal idea identifiable as the "anima motrix" of Plato, "vis" in Newtonian and Cartesian physics and "Kraft" (strength) in the writings of German scientists of the nineteenth century. Starting with the same thematic content, scientists projected the idea of force onto the phenomenic-analytic plane in different ways. Thus, the notion of force for scholastic physicists started with the thema of anima motrix, concentrated on the phenomenic aspect of continuous terrestrial motion against a constant retarding obstacle and gave little analytic content beyond a qualitative idea of magnitude. Motion of a body was seen within a broader framework in which the natural state of an earthly body was one of rest. For that reason, a frictionless world in which bodies could move without resistance was an incredible idea. Meanwhile, Galilean physics started with apparently the same thematic content but invested the idea of force with the phenomenic ideas of an object sliding along a frictionless plane and the analytic idea of vector mathematics. Thus we see physicists of the seventeenth century constructing two very different notions of force. Yet, because they shared the thema of anima motrix, or vis, they claimed to be talking about the same thing.

With the aid of thematic analysis it is possible to trace the evolution and convolution of ideas in science. The evolutionary versus static cosmological view prevalent in Greek thought is still discernible today in modern cosmology. The notion of atomism - based on a thema of discontinuity - can be opposed to the idea of continuity - based on a thema of uniformity. Other thema often occurring in science are: order (and disorder), simplicity (and complexity), infinite (and finite), universality, symmetry and so on. It is also interesting to note the number of thema which exist in opposing pairs or in triadic form. In this respect Holton's themata bear a strong resemblance to Kant's antinomies of pure reason.

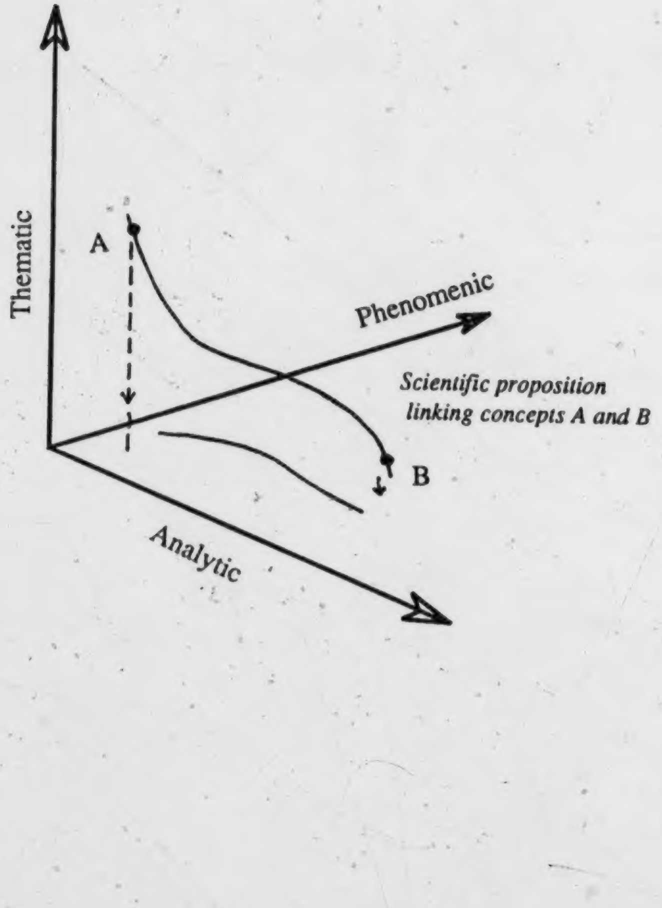
Thematic
A
Phenomenic
Scientific proposition
linking concepts A and B
B
Analytic

Figure 3.2 Proposition space augmented by the thematic dimension of scientific ideas. In Holton's model, "traditional" scientific discourse always involves a projection of propositions back onto the phenomenic-analytic plane.

3.3 The Nature of Themata

The themata of science are remarkably robust and few in number. Holton suggests that there are fifty or so and that they often appear in dyadic or triadic form. Why should this be? Of all the possible ways in which creative - scientific thought can and does move, why is it that a finite number of thematic elements appear to describe the whole? While the answer to this question is not the burden of this thesis, it is tempting to explore the following connections.

Kant, in Critique of Pure Reason, addresses the problem of how the mind comes to experience the world. In particular, Kant begins his critique with the remark:

> ... it is quite possible that our empirical knowledge is a compound of that which we receive through impressions and that which the faculty of cognition supplies from itself..(15).

In stating this, Kant begins a long and difficult discussion of a priori (pre-experiential) knowledge. In so doing, Kant introduces his **categories**(16) (of quantity, quality, relationship and modality) as "the true primitive conceptions of the pure understanding(17)." Kant's categories bear a striking resemblance to many of Holton's themata. In a later section of the Critique, Kant points out a "natural and unavoidable dialectic of pure reason" and soon after develops the four antinomies(18) (one for each category).

It is tempting to relate Kant's categories and antinomies to the themata found by Holton. The thema of discreteness as opposed to the thema of continuum, for example, figured prominently in the early years of quantum theory. These themata seem very close to Kant's antinomy of quality (every composite substance is composed of simple parts (discreteness); no composite substance is composed of simple parts (continuum)). The very same themata played a prominent role in other discussions in science (ie., the wave-particle debate of the 18th century or the acceptance of atomic theory in the 19th century). In the 20th century the wave-particle duality of quantum physics in which matter is viewed as having both wave and particle characteristics would seem to be a synthesis of these antithetical positions.

The Kantian antinomy of quantity, for example, can be related to thematic struggles in astronomy and cosmology concerning the question of whether the universe is finite or infinite in space and time. An example of this is found in the big-bang and steady state cosmological models(19). The modern big bang models derive from a suggestion made in 1946 by George Gamow. Gamow suggested that the universe emerged from a hot, infintely dense state at a finite point in time - perhaps 15 to 20 billion years ago. According to this widely accepted model, the universe is finite but unbounded. At approximately the same time that Gamow put forward the big bang model, Bondi, Gold and Hoyle suggested a radically different view - the steady state cosmology. In this view, the universe is infinite in both spatial and temporal extent having neither boundary nor epoch of origin. Matter, in the form of neutrons, is created continuously within this model and can appear spontaneously anywhere in the universe. Although the steady state cosmology was considered as a serious rival of the big bang theory, evidence has been accumulating since the mid 1960's which seriously weakens this theory. The most significant contradictory evidence is the discovery made in 1965 by Penzias and Wilson that the universe is bathed in a uniform microwave glow. This, presumably is the remnant of the intense energy released during the big bang. At the present time, although the steady state theory is not "dead", it has only a small number of supporters.

At the core of the steady state model is an assumption known as the **perfect cosmological principle** which asserts that the universe appears the same to observers at any point in space or time. This implies that the universe must be infinitely old - ie. no beginning. The perfect cosmological principle is an extension of an assumption called the **cosmological principle** which is supported by most cosmologists. This weaker statement holds that the universe appears to be the same regardless of spatial location in the universe. Whether one accepts both of these principles or only the latter cosmological principle is a matter that cannot be supplied solely by the phenomena themselves. The choice ultimately contains a thematic aspect. That some cosmologists doggedly hold to the perfect cosmological principle and the steady state model in the face of strong, contradicting evidence suggests the power of themata.

The themata of determinism versus indeterminism have played a significant role in 20th century physics. These themata seem to be closely related to the Kantian antinomy of relation which contrasts strict causality with freedom. Are the laws of the universe regular and predictable or do they possess an intrinsically probabilistic (ie. free) aspect? Such a question was of singular importance during the formative years of quantum physics and formed the backdrop against which Einstein and Bohr argued over the meanings of quantum mechanics.

In relating the themata to Kant's categories and antinomies we would place the themata within a philosophical framework and begin to account for their finite number. We are still left, however, with the problem of explaining how the intellect actually recognizes and applies the categories to sense impressions. Kant ascribes this capacity to our mother-wit(20), and contends that our intelligence "is a skill so deeply hidden in the human soul that we shall hardly guess the trick that Nature here employs.(21)" Kant's reluctance to probe beyond "mother-wit" is shared by many other philosophers

The origin or logic of Holton's themata is usually brushed aside as a "problem for psychology". Michael Scriven, for example, suggests that the problems of logic in science can

> ...only be solved by reference to concepts previously condemned by many logicians as "psychological not logical", e.g. understanding, belief, and judgment.(22)

If not discounted as a problem of psychology, the origin of the thematic dimension of science is simply asserted to be a problem that transcends understanding. For example, Karl Popper writes on scientific discovery and the non-phenomenic-analytic plane aspects of science:

> Science is not a system of certain, or well established statements; nor is it a system which steadily advances towards a state of finality ... We do not know: we can only guess. And our guesses are guided by the unscientific ... faith in laws, in regularities which we can uncover-discover. Like Bacon, we might describe our own contemporary science-"the method of reasoning which men now ordinarily apply to nature" -as consisting of "anticipations, rash and premature" and as "prejudices".(23)

In a similar vein, Bertrand Russell states:

> I have come to accept the facts of sense and the broad truth of science as things which the philosopher should take as data, since, though their truth is not quite certain, it has a higher probability than anything likely to be achieved in philosophical speculation.(24)

Elsewhere, Russell admits

> ... the premises of science turn out to be a set of presuppositions neither empirical nor logically necessary.(25)

Holton's discussion of the thematic dimension of science is essentially an empirical one. He has shown through many case studies the reality of themata and the fundamental role they play in science. Accounting for these themata in a philosophical sense has led to some of the most basic questions concerning the nature of science. The reluctance of philosophers to push the analysis beyond these questions prompted Michael Polanyi to write

> ... one may wonder too that generations of scholars have left such an ultimate submission of reason to unaccountable decisions unchallenged. Perhaps both Kant and his successors instinctively preferred to let such sleeping monsters lie, for fear that, once awakened, they might destroy their fundamental conception of knowledge. For, once you face up to the ubiquitous controlling position of unformalizable mental skills, you do meet difficulties for the justification of knowledge that cannot be disposed of within the framework of rationalism.(26)

Polanyi's reference to "sleeping monsters" is a direct challenge to the pervasive acceptance of the ideal of detached knowledge which runs through much of modern philosophy, science and science education. Holton's demonstration of the role of themata in science provides us with a glimpse that perhaps the ideal of detachment is, ultimately untenable. Instead, we see that the beliefs and presuppositions of scientists, although perhaps hidden from direct view, are none the less active and vital parts of science. All knowledge possesses an essentially personal component. The challenge that lies ahead is to demonstrate the breadth of Polanyi's ideas and their implications for science education and how it is manifest in the work that I do as an astronomer and teacher.

3.4 Objectivity

Perhaps, in the popular understanding at least, the most significant difference between the sciences and the humanities lies in the notion that science is, or has the potential to be, "objective". This point is strongly made by Israel Scheffler in the introduction to a series of essays defending the ideal of objectivity against a mounting tide of subjectivism in science:

> A fundamental feature of science is its ideal of objectivity, an ideal that subjects all scientific statements to the test of independent and impartial criteria, recognizing no authority of persons in the realm of cognition.(27)

But what precisely does "objective" mean when used in this way? In the most blatant stereotype, the objective scientist appears as an emotionally emptied, detached individual -able to drop an idea without reluctance when the data demand it (the naive falsificationist position). Scheffler concludes that "the cold and aloof scientist, is, then, a myth(28)". Instead, Scheffler suggests that scientists are as variegated in personality and cognitive style as any other group of people. Science is objective because scientists are committed to the idea of "fair controls"(29). Fair controls would be externally imposed criteria that carry the sanction of the scientific community. These controls are malleable and change in response to their application and enlargement by the scientific community.

Scheffler's view of objectivity ultimately rests on the belief in the detachment of the individual or individuals from the ideas of science and of their commitment to the application of fair controls. Objectivity is an ideal, a limiting case to which science tends. Scheffler's discussion of objectivity is very similar, in essence to Popper's notion of a third world of public knowledge. Both of these positions are powerful rejoinders to the naive subjectivism that, according to Scheffler would assert that:

> ... theory is not controlled by data, but that data are manufactured by theory; that rival hypotheses cannot be rationally evaluated, there being no neutral court of observational appeal nor any shared stock of meanings; that scientific change is a product not of evidential appraisal and logical judgment, but of intuition, persuasion, and conversion; that reality does not constrain the thought of the scientist but is rather itself a projection of that thought.(30)

While Scheffler's view of objectivity cannot be completely dismissed, neither can it be completely accepted. Implicit in Scheffler's view is the acceptance of the belief in the ideal of detached knowledge - of Popper's knowledge without a knowing subject. This brings us back to one of Polanyi's "sleeping monsters" for, it would seem, Scheffler is content to leave our ability to establish **commitment** as an unformalizable skill. As well, Scheffler's notion of objectivity does not have enough scope to account for Holton's demonstration of the thematic dimension of science. Even before a commitment to the ideal of "fair control" is made the scientist possesses a thematic orientation to reality.

Michael Polanyi offers a different view of objectivity. As an example, Polanyi considers the Copernican shift from geocentrism to heliocentrism. It is tempting to suggest that the Copernican cosmology is more objective than its predecessor because humankind no longer occupies a favoured (central) position in the universe. If, however, the essence of the objectivity of the Copernican theory lay in seeing mankind in "proper" relation with respect to the rest of the universe then, compared to the vastness of spacetime, we should be more concerned with vast clouds of interstellar dust than the mere speck humanity represents in the universe.

The Copernican cosmology is more objective than its Ptolemaic predecessor for a much different reason. Although the original form of the Copernican theory offered little or no compelling observational reasons of its superiority over the Ptolemaic cosmology, it did offer a simpler, more universal cosmology. Its increased objectivity lay in the intellectual satisfaction and appeal to rationality offered by the Copernican cosmology. Faced with the choice between the dictates of his eyes - that the Sun moves across the sky - or the appeal of his reason, Copernicus wrote:

> I find it much more easy to grant that [the heliocentric hypothesis] than to unhinge the understanding by an almost infinite multitude of spheres-which is what those who keep the earth at the center of the world are forced to do. But we should rather follow the wisdom of nature, which, as it takes very great care not to have produced anything superfluous or useless, so it often prefers to endow one thing with many effects.(31)

Copernicus' appeal to reason is based on an implicit notion of economy and simplicity that goes beyond the evidence of the senses. Polanyi concludes:

> It becomes legitimate to regard the Copernican system as more objective than the Ptolemaic only if we accept this very shift in the nature of intellectual satisfaction as the criterion of greater objectivity.(32)

We find in this view of objectivity an essential difference between Michael Polanyi's theory of knowledge and that of Scheffler and other contemporary philosophers and educators. Objectivity cannot be placed solely outside of the individual (ie. external "fair controls"). Neither are we being objective when we attempt to eliminate ourselves from the act of knowing. We are ineluctably faced with our participation in making any knowledge claims about the world and in ascribing greater or lesser objectivity to these claims.

Polanyi cites many examples from the history of science to demonstrate the role that intellectual satisfaction plays in giving meaning to the term "objectivity". Perhaps one of the most compelling examples is provided by the Michelson-Morley experiment and Einstein's theory of relativity. The Michelson-Morley experiment was performed in the 1880's and 1890's and was expected to reveal the motion of the Earth through the ether.(33) The results of the experiment were disturbing; the velocity of the Earth through the ether was much less than expected. Within a few decades physicists accepted this as a result explained fully within Einstein's theory of special relativity. Even more interesting, however, is the manner in which the Michelson-Morley experiment is "reconstructed" in modern textbooks. A commonly held view is that the Michelson-Morley experiment was an empirical precursor to Einstein's theory of special relativity. This view has been discredited by many writers - most notably Einstein himself(34).

A more persistent and erroneous presentation of the Michelson-Morley experiment centres around the size of the measurements of the Earth's motion implied by the experiment. Almost all modern textbooks contain passages like the following:

> ... they found no significant fringe shift. They set up their apparatus at various orientations. They made observations day and night, so they would be at various orientations with respect to the sun. They tried at different seasons of the year. Never did they observe a fringe shift.(35)

In fact, a measurable fringe shift was detected which implied an ether drift on the order of 8 to 9 km/s. In a series of experiments performed between the years 1902 to 1926, D.C. Miller and collaborators continued to record fringe shifts.

Why is this well documented historical fact ignored by so many writers? While it could be ascribed to one's ignorance of the Miller experiment the reason probably hinges on the term "significant". Even though Einstein's theory had few experimental supports, Miller's experimental results did not damage the growing status of Einstein's theory. According to Polanyi this is precisely because Einstein's theory has a strong appeal to our sense of rationality in nature. It made sense to ascribe Miller's results to some other, as yet unaccounted for source of error. It is also worth noting that modern "re-enactments" of the Michelson-Morley experiment show **no excess** fringe shifts (to a precision of less than 1 part in 10^{15}) - thereby removing the anomaly reported by Miller.

Just as the observational problems attending the Copernican system could not detract from the intrinsic rationality of the system over against its predecessor, neither could Miller's data persuade physicists to give up the more intellectually satisfying vantage point offered by Einstein's theory.

In a sense, Polanyi does agree with Scheffler; the objectivity of science does arise through the acceptance of "fair controls". The crucial difference, however, between Polanyi and Scheffler has to do with the nature of commitment. In Polanyi's view it is only through a passionate, rigorous and inescapably personal pursuit of rationality that one can hold such a commitment to "fair controls". In a similar vein, Thomas Kuhn(36) expands on the essential role that commitment must play in science. For both Polanyi and Kuhn, such commitments are not capricious or subjective but neither can they be completely disentangled from the presuppositions held by the individual.

Notions of objectivity that in the end strip away the human in search of an impersonal application of method are, in Polanyi's view, symptomatic of an implicit belief in the existence of wholly explicit, impersonal knowledge and led Polanyi to assert that:

> ... the prevailing conception of science, based on the disjunction of subjectivity and objectivity, seeks - and must seek at all costs - to eliminate from science such passionate, personal, human appraisals of theories, or at least to minimize their function to that of a negligible by-play. For modern man has set up as the ideal of knowledge the conception of natural science as a set of statements which is 'objective' in the sense that its substance is entirely determined by observations, even while its presentation may be shaped by convention. This conception, stemming from a craving rooted in the very depths of our

> culture, would be shattered if the intuition of rationality in nature had to be acknowledged as a justifiable and indeed essential part of scientific theory.(37)

Polanyi's view of objectivity underscores the crucial role that the personal dimension of science plays in our understanding the term 'objectivity' as it applies to science. Holton's thematic analysis supports this conclusion and challenges science educators to articulate the sense in which science can be said to be objective.

3.4 Tacit Knowing

"We know more than we can tell" is a phrase that succinctly summarizes Polanyi's thesis of tacit knowledge. As we have already seen, our evidence of scientific knowing vis a vis propositional statements (Holton's phenomenic-analytic plane) is pre-figured by thematic elements or predispositions. Polanyi goes beyond the thematic to assert that our declarations of knowing are explicit articulations of knowledge implicitly (tacitly) held.

It is the tacit structure of knowledge that forms the central pivot of Polanyi's epistemology. In developing the thesis of tacit knowing, Polanyi considers the analogous structure of four processes of knowing: (1) understanding physiognomies, (2) performance of skills, (3) the use of the senses, and (4) the mastery and use of tools. For each of the four cases listed we can be either subsidiarily (or a-critically) aware of particulars or focally aware of particulars. In recognizing a familiar face we are subsidiarily aware of the particulars of the physiognomy while focally attending to the whole. It is an act of tacit inference that unites the many particulars of a face into the whole that we recognize. An experienced astronomer, looking at a raw(38) light curve from a short period variable star, focally attends to the curve itself (ie: points of maxima or minima, evidence of multiple modes, etc.) while being subsidiarily aware of random noise or systematic effects due to the atmosphere. The student (apprentice), on the other hand, may be focally aware of the individual data points on the curve or of random scatter in the curve and fail to see the curve at all. In both cases the astronomer and student are attending to the same phenomenon but they bring to bear different tacit understandings of what it is that they see.

The process of moving **from** a subsidiary awareness of particulars **to** a focal awareness of an integrated whole is the archetypical structure of knowing in Polanyi's philosophy. The **from-to** relationship characterizes not only the act of of knowing but knowledge itself:

> Knowledge is an activity which would better be described as a process of knowing. Indeed, as the scientist goes on inquiring into yet uncomprehended experiences, so do those who accept his discoveries as established knowledge keep applying this to ever changing situations, developing it each time a step further. Research is an intensely dynamic inquiring while knowledge is a more quiet research. Both are ever on the move ...(39)

The basic from-to structure of knowledge prefigures the tacit-explicit form in which we can be said to hold knowledge. It is through the use of lanquage (verbal, mathematical as well as all other forms of symbolic representation) that we affect the transformation of tacit level knowledge into explicit knowledge. It is through the articulation of knowledge made possible by language that our intellectual superiority over other animals is realized but Polanyi goes to great pains to demonstrate that our articulation can never be exhaustive and must be seen in relation to the following three areas:

(1) The area where the tacit predominates to the extent that articulation is virtually impossible; we may call this the **ineffable domain**.

(2) The area where the tacit component is the information conveyed by easily intelligible speech, so that the tacit is co-extensive with the text of which it carries the meaning.

(3) The area in which the tacit and the formal fall apart.... There are two extremely different cases of this, namely (a) an ineptitude of speech ... (b) symbolic

operations that outrun our understanding and thus anticipate novel modes of thought. (40)

As an example of the first area of ineffable knowledge Polanyi cites his ability, at a glance, to pick out his raincoat from a crowd of similar garments or his ability to ride a bicycle. Although he cannot tell how he performs these acts he is none the less perfectly capable of performing them. On a more serious note, Polanyi describes the education of a medical diagnostician as a clear demonstration of the function of ineffable knowledge. One cannot explain how to "read" an x-ray or electrocardiogram. While rules of thumb can be offered, the student becomes a diagnostician only by practice under the tutelage of an accomplished teacher. It is within the ineffable domain that we acquire the sense of judgment and intuition that accompanies our explicitly held knowledge and points toward the more general notion of **connoisseurship** (to which we will return in a later chapter). It is also in the ineffable domain that we find Holton's allusion to the role that thematic predispositions play in science.

Polanyi's second area of interplay between the tacit and the articulate is precisely that of everyday, casual speech. Examination of the transcripts of a classroom conversation between a student and a teacher or of the conversation among a group of friends reveals just how fragmentary and grammatically incomplete our conversations are. Programming a computer with such lack of clarity would be futile (indeed, one goal of artificial intelligence research is to make computers more flexible along just these lines.) In this realm, the tacit understanding "carries" the conversation.

In the third area of interplay between tacit and articulate knowing Polanyi points toward an essential feature of his philosophy. Our symbolic representation can sometimes extend much farther than we can see. Copernicus did not foresee the work of Newton yet his theory anticipated Newton. At the core of this is Polanyi's view of realism and that we can make contact with an independent reality. Scientific theories can have a vectoral nature that points, in a yet un-articulated way, to a future and more encompassing theory. This, Polanyi would claim, is the appeal to rationality that characterizes his notion of the greater objectivity that one theory may have over another. Clearly, however, theories can be wrong and our symbolic representations can be misleading. As Polanyi concludes:

> The mind which entrusts itself to the operation of symbols acquires an intellectual tool of boundless power; but its use makes the mind liable to perils the range of which seems also unlimited. The gap between the tacit and the articulate tends to produce everywhere a cleavage between sound common sense and dubious sophistication, from which the animal is quite free.(41)

As Holton has pointed out scientists are rarely conscious of the thematic component of their science and he suggests that the scientists of genius are those who

> are particularly "themata prone", and who have the necessary courage (or folly?) to make decisions on thematic grounds.(42)

It would seem that Holton's "themata proneness" is a conjunction of the first and third of the tacit-articulate areas described above. The scientist of genius seems to be able to follow a hunch -often based on perilously little data. For example, consider Holton's(43,44) analysis of the work of Robert Millikan. Despite Millikan's claim that he used all of the data collected in his famous oil drop experiments, Holton has shown that in fact Millikan used only 40% of his data, systematically rejecting data that (at least in hindsight) would contradict the hypothesis of a fundamental unit of charge. This may be discounted as fraudulent science but doing so would miss a great deal. Millikan's rejection of data can be understood as his practiced judgment, his use of ineffable powers of discernment that any good experimental scientist must have to wade through "noise" in the search for a signal. As Holton suggests, it is likely that Millikan, albeit guided by his thematic disposition, did not even consider the rejected data as being "true" data - it was contaminated by one of innumerable possible sources of error. Thus, in Millikan's own mind no selection of data was taking place.

Knowing cannot be conceived, in Polanyian terms, as a passive state. To know is to grapple with and participate in the essential from-to structure of knowledge. As we do so we are unaware of the many subsidiary factors at play in our thinking. In Polanyi's terms, we **dwell in** these tacitly held particulars as we comprehend the whole.

3.5 Indwelling

A good shoe, it could be argued, is one of which we are not aware. Aside from the obvious pun, we **dwell in** that shoe in a way that an ill fitting shoe would not allow. Our awareness of the good shoe is subsidiary. The shoe has been subsumed by our body; we indwell the shoe. A pinching shoe, on the other hand continuously commands our attention. We are always focally aware of our foot within the shoe. Polanyi's concept of indwelling can be applied to all levels of knowing from the performance of simple skills and tasks to the utilization of the most abstract of scientific theories. In our use of a hammer we are unaware (explicitly) of the feel of the hammer on the palm. Similarily, the blind man's cane becomes an extension of the hand in the operation of the from-to structure of knowing through which the man explores his environment.

Just as we have only a subsidiary awareness of our good shoe in which we dwell, a scientist has only a subsidiary awareness of the presuppositions (themata) of his or her indwelling. Polanyi takes the process of indwelling to be characteristic of all applications of the from-to relation. He asserts that:

> When we accept a certain set of pre-suppositions and use them as our interpretive framework, we may be said to dwell in them as we do in our own body. ... It is by his assimilation of the framework of science that the scientist makes sense of experience. This making sense of experience is a skillful act which impresses the personal participation of the scientist on the resultant knowledge.(45)

Gerald Holton has aptly described indwelling in stating:

> He (the scientist) proceeds through his problem like an explorer through a jungle, sensitive to every clue with every faculty of his being. Indeed, some of the greatest theoretical scientists have stated that during those early stages of their work they do not even think in terms of conventional communicable symbols and words.(46)

It is by dwelling in the particulars of a phenomenon that meaning of the phenomenon arises. For Polanyi the act of indwelling is the locus of all meaning. Holton's thematic analysis of science fits naturally within the broader framework of indwelling. From the vantage point provided by Polanyi we now see that the thematic extension of science is, fundamentally, an intrinsic and non-reducible part of science. Even in the phenomenic-analytic plane itself we still find the personal engagement of the scientist as he or she indwells the science.

3.6 Conclusion

In the previous sections the idea has been developed that science contains an unavoidably personal dimension. Despite the scientist's straining for clarity and public consensus (the "party line"), the personal engagement of the individual cannot be ignored if we are to acquire any significant understanding of what science is. Holton, Polanyi, Kuhn (and others) have shown the extent that thematic orientations play in science. Polanyi goes farther, to suggest that the very nature of knowledge is personal and the ideal of impersonal knowledge is false.

In the following chapters the discussion will shift to a more pedagogical focus. How will the recognition of personal science and Polanyi's conception of knowledge influence science education? In exploring this question the central thrust of this thesis will emerge - that the nurturing of one's personal science must be a vital part of the learning of science. In the next chapter attention will focus on how, within the curriculum, personal science can be communicated. In chapter seven the educational implications of personal science and its relation to Polanyi's philosophy of knowledge will be explored.

Notes - Chapter Three

1 International Astronomical Union Colloquium 107, Algols hosted by the University of Victoria and the Dominion Astrophysical Observatory, Victoria, British Columbia, Canada, August 15-19, 1988.

2 It is now acknowledged, on the basis of measurements of the velocities of stars orbiting galactic nuclei as well as the dispersion velocities of galaxies within clusters of galaxies, that a great deal of the matter present in galaxies is not visible to us - ie. missing mass. The missing mass problem ranks as one of the most significant problems in astrophysics today.

3 The suggestion has been made that in the early evolution of galaxies the conditions were right for the formation of very low mass stars (less than 0.1 solar masses). Such dwarf stars would be subluminous - hence the name brown dwarfs. They have been suggested as a possible solution to the missing mass problem.

4 Washburn, M. **Sky and Telescope, Vol 76. 6**, 1988, pp. 628-630. In 1986, the American physicist Louis Franks suggested that the earth is being bomdarded at a continuous rate (approximately one every 3 seconds) by "minicomets". Such minicomets would consist primarily of ices and have masses on the order of 100 tonnes. Frank's theory has been severely criticised and at times the criticism has been as much a criticism of Frank himself as of his theory.

5 Holton, Gerald J.The Thematic Origins of Scientific Thought revised edition Cambridge, Mass.: Harvard University Press, 1988.

6 Holton, Gerald J. The Advancement of Science and Its Burdens.Cambridge, Mass.: Harvard University Press, 1986, pg. 6.

7 In choosing the photomultiplier and filter (standard UBV filters in this case) I am restricting my observations to the visible region between 350 nm to 650 nm and to stars with visual magnitudes betwen roughly 5 and 9. My choice of stars or other objects to observe must be compatible with this equipment. If, for example there are significant effects causing emission of light in the near infra-red (roughly 700 nm and longer) I would not see it. Hence I will choose my objects on the expectation that they will be "interesting" in a way compatible with the equipment.

8 In 1985 a group of Canadian amateur astronomers reported seeing, on separate occasions, several bright (V = 0 mag) flashes coming from the constellation Aries. A brief note appeared in the popular journal **Sky and Telescope**, July 1985, pg 54 describing these observations. Subsequent to this Sky and Telescope received many similar reports of flashes from all regions of the sky. How much credence should a professional astronomer give this? Clearly the editor of the Astrophysical Journal Letters felt that the observations of the original group were credible enough to communicate to the astronomical community (Ap.J. Letters, August 1,

1986.) Follow-up observations by astronomers at the U.S. Naval Observatory were unable to detect "flashers".

9 Halton Arp, Quasars, Redshifts and Controversies (Berkeley, Interstellar Media 1987). In this book Arp discloses that his views have led to his "ostracism" from extra-galactic astronomy in the U.S. Although a world renowned astronomer, Arp's research was deemed unacceptable to the telescope allocation committees of Mount Wilson, Las Campanas and Mount Palomar observatories. Arp was informed that he would be granted no observing time at the major U.S. observatories. Since then he has moved to the Max Planck Institute for Physics and Astrophysics in Garching, West Germany where he continues his research on quasars.

10 The most common understanding of gravitation is that matter and energy cause a "warping" of the structure of spacetime. Spacetime is no longer Euclidean and the apparent attraction of one object to another can be viewed a consequence of the motion of the bodies through curved spacetime. In the words of John Archibald Wheeler (one of the co-authors of Gravitation - the definitive graduate text on the subject):

> Matter tells space how to curve
> Space tells matter how to move

Despite this convention, consistent gravitational theories can be constructed in a flat spacetime. This requires, however, the construction of a much more complicated force law between the gravitating bodies.

11 Robert W. Smith. The Great Debate Revisited. **Sky and Telescope** vol. 65, no. 1, pg 28, January 1983. Shapley's revised figures for the size of the Galaxy were too large by a factor of about two. The current best estimate for the size of the Milky Way Galaxy gives it a diameter of 120 000 light years and places the sun on one of the spiral arms, approximately 33 000 light years from the galactic center.

12 S. Chandrasekhar, Truth and Beauty (Chicago: University of Chicago Press, 1987) pp. 130-137.

13 The white dwarf phase is one of the final stages through which a star will evolve. Chandrasekhar has shown that, provided a star has a mass of less than roughly 1.5 times the solar mass it will eventually exhaust its supply of fuel and slowly contract to form a small initially white dwarf. Over eons the white dwarf will slowly cool and eventually become a black, invisible dwarf star. Current theory suggests that the cool down time for a white dwarf is of a time scale comparable to the age of the universe. If a star's mass exceeds 1.5 solar masses it will collapse to become a neutron star or possibly a black hole. For a comprehensive review of the ideas presented here see: Israel, W. "Dark stars: the evolution of an idea", in 300 Years of Gravitation, ed. S.W.Hawking and W. Israel. New York: Cambridge University Press, 1987.

14 Holton, pg. 6.

15 Immanuel Kant. The Critique of Pure Reason (second edition) London: Guernsey Press, 1984, pg. 25.

16 The following is a tabulation of the categories considered by Kant:
Categories of:
Quantity(unity, plurality, totality)
Quality (reality, negation, limitation)
Relation of
    inherence and subsistence
    causality and dependence
        community
Modality of
    possibility and impossibility
    existence and non-existence
    necessity and contingence

17 Kant, p. 25.

18 These antinomies are:

Antinomy of Quantity:

Thesis: The world is finite in space and time.

Antithesis: The world is infinite in space and time.

Antinomy of Quality:

Thesis: Every composite substance is composed of simple parts. Everything that exists is either made up of these simple parts or is a simple part.

Antithesis: No composite thing is composed of simple parts. Nowhere in the world is there such a simple part.

Antinomy of Relation:

Thesis: Causality according to the laws of nature is not the only law of causality operating to originate the phenomena of the world. A causality of freedom is also necessary to fully account for these phenomena.

Antithesis: There is no such thing as freedom, but everything in the world happens solely according to the laws of nature.

Antinomy of Modality:

Thesis: There exists a necessary being.

Antithesis: An absolutely necessary being does not exist.

The categories represent the mind's innate (a priori) ability to receive sense impressions and act on them. In doing this Kant appears to offer a solution to the problem of how we can know anything about the external world. The antinomies are fundamentally undecidable pairs of propositions that occur in pure (not empirically grounded) reason.

19 see Narlikar, J.V. Introduction to Cosmology. Boston: Jones and Bartlett, 1983, pp. 253-270.

20 This quotation appears in the first edition of Kant's critque, pg 133

21 Kant, pg 141.

22 Scriven, Michael."Explanations, Predictions and Laws". Minnesota Studies in the Philosophy of Science, III. Minneapolis: University of Minnesota Press, 1962, p. 172.

23 Popper,Karl R. The Logic of Scientific Discovery New York: Basic Books, 1959, p.278.

24 Egner,Robert and Denonn, Lester eds.,The Basic Writings of Bertrand Russel (New York, Simon and Shuster 1967), p. 658.

25 Russell, Bertrand .Human Knowledge, Its Scope and Limits (London, Allen and Unwin, 1948), part 6, chap. 2.

26 Grene, Marjorie ed. Knowing and Being, essays by Michael Polanyi (Chicago: University of Chicago Press, 1969), p.106.

27 Scheffler, Israel. Science and Subjectivity Indianapolis: Bobbs-Merrill, 1967, p. 1.

28 Scheffler, pg. 2.

29 Scheffler does not expand on the idea of fair controls beyond stressing the communal nature of scientific discourse. Fair controls are seen as embodiments of the institutions and traditions of science. This, unfortunately seems to undermine Scheffler's notion of objectivity for it begs the question of the origin of the traditions in science. In a curious way, Scheffler attachs Kuhn for relativizing science - yet Kuhn, in developing the paradigmatic understanding of scientific institutions, seems to have provided a clearer understanding of what "fair controls" means in practice.

30 Scheffler, pg. v.

31 Copernicus, Nicholas. (1947) On the Revolutions of the Celestial Spheres. in The Philosophers of Science, eds. Saxe Commins and Robert Linscott, Random House: New York, pg 68.
The Copernican system was intended to restore cosmology to one of motion based on pure circles. In order to agree with observation, the Ptolemaic system was forced to introduce a system of smaller circular motions some of which were not centred on the earth but on a point on the circular orbit and on a point off set from the earth. The result was noncircular motion for a planet with respect to the earth. The Ptolemaic system was able to reproduce the observed motions of the planets to the precision of the observations of the day. While the Copernican system could also predict the positions of the planets with similar success, it suffered from a number of defects. The most glaring of which was the apparent absence of parallax in the background stars - a natural consequence to be expected if the earth itself were moving. Thus, the Copernican system was not manifestly superior to its predecessor.

32 Polanyi, Michael. Personal Knowledge (Chicago: The University of Chicago Press, 1958) p. 4.

33 In the Micheslon-Morley experiment a light beam was split into two beams which travelled at right angles to each other. One of the beams was oriented across the

velocity vector of the earth while the other beam was parallel to the earth's motion. When the beams recombined any influence of the earth's motion on the propagation of light would result in interference between the combining beams.

34 The extent to which Einstein was influenced by the Michelson-Morley experiment has been complicated by inconsistencies in Einstein's own discussion of this point. A thorough discussion of this is found in Holton's Thematic Origins of Scientific Thought, pp. 279-370. Although it is unlikely that the M-M experiment was in any way a crucial point in the development of the theory it certainly acts as an important step in one's personal acceptance of the the special theory of relativity.

35 Douglas C. Giancoli, General Physics (Englewood Cliffs: Prentice-Hall, 1984) p.750.

36 Kuhn, Thomas. The Structure of Scientific Revolutions revised edition. Chicago: The University of Chicago Press, 1970, p. 42.

37 Polanyi, pp. 15-16.

38 By "raw" light curve I mean the graph of light variation in the apparent brightness of the star uncorrected for peculiarities of the equipment or gross effects of the atmosphere. Such curves are often constructed to get a feeling (a tacit appreciation) of the quality of data.

39 Michael Polanyi, "Knowing and Being" from Knowing and Being: Essays by Michael Polanyi, ed. Marjorie Grene. (Chicago:University of Chicago Press, 1969), p. 132.

40 Polanyi, Personal Knowledge, p.87.

41 Polanyi, Personal Knowledge, p.94.

42 Holton, Gerald J.The Thematic Origins of Scientific Thought revised edition (Cambridge, Mass.: Harvard University Press, 1988) p.47.

43 Holton, pg. 453.

44 Holton, Gerald J.The Scientific Imagination: Case Studies. New York: Cambridge University Press, 1978.

45 Polanyi, Personal Knowledge, p.60.

46 Gerald Holton and Stephen G. Brush, Introduction to Concepts and Theories in Physical Science 2nd edition, (Reading: Addison-Wesley, 1973) p.188.

Chapter Four

The Sharing of Personal Science and the Narrative Element in Science Education

4.1 Introduction

> *I like to use a little anecdote because this particular thing happened to me when I was a kid. My friend and I had been playing on a merry-go-round but had rigged it up with a poplar pole so that the merry-go-round had a radius of maybe 25 feet instead of the usual 4 or 5 feet. He started pushing this thing on the inside, and I'm sitting on the end of the poplar pole going about nineteen times as fast (an exaggeration) and I decided that this was more than I could stand, so I decided to let go. At the time I let go I had no clear idea what would happen to me. Perhaps I would land on my feet, run a few steps and slow down. In actual fact I went sailing straight out and landed in a bush. Okay, I didn't go straight out this way, and I didn't go inward, but the last thing I remember before I let go was this patch of bush straight ahead of me. So it was like a revelation, I suddenly understood what would happen if you were travelling in a circle and let go; you move straight in the direction you were going. I know it's only anecdotal but it seems to convince students better than a demo or doing the mathematical derivation*

With this simple anecdote a teaching colleague of mine employs one of the oldest modes of communication, the story, to illuminate a point in classical mechanics. A story, with just a few well chosen words, can draw in the reader or listener and create a world of shared experience. The story can at times communicate in few words that which a dense, technical analysis might require many lines to accomplish. There are some things that perhaps only a story can communicate especially when one enters the realm of ineffable knowledge or tacitly held understandings.

In this chapter the use of narrative(1) as a vehicle for indwelling, for sharing, communicating and understanding personal experience will be explored. It will be argued that the narrative is a useful (and at times powerful) form of expression that is too often neglected in science education. Indeed, the narrative mode is esential to a science education that values the belief that students must have a personal engagement with the ideas they are to learn. Stories are our natural means of sharing in the lives of others and of more fully exploring meaning in our own. Through stories students may more successfully begin to see the subtle dimensions of science and of understanding the ways in which science, culture and world view interact.

4.2 The Aesthetic Mode of Knowing in Science Education

A mode of knowing (and thought) can be considered to be a way by which a person orders, structures and forms his or her experience of reality. Form giving is a characteristic of all shared human activities from art to literature to science. As Elliot Eisner puts it:

> I do not wish to suggest that the aesthetic is restricted to the fine arts and literature. All scientific inquiry culminates in the creation of form: taxonomies, theories, frameworks, conceptual systems. The scientist, like the artist, must transform the content of his or her imagination into some public, stable form, something that can be shared with others. The shape of this form -its coherence- is a critical feature concerning its acceptability. The adequacy of theory is not simply determined by experimental results. Experimental results can often be explained by competing theories. The attractiveness of a theory is a central factor in our judgment of it.(2)

Attractiveness in science is often expressed in terms of "beauty", "elegance" or "simplicity". Henri Poincaré expresses this in the following passage from Science and Method:

> The scientist does not study nature because it is useful; he studies it because he delights in it, and he delights in it because it is beautiful. ... Of course, I do not here speak of that beauty which strikes the senses, the beauty of qualities and appearances; not that I undervalue such beauty, far from it, but it has nothing to do with science; I mean that profounder beauty which comes from the harmonious order of the parts and which a pure intelligence can grasp(3).

The aesthetic mode, as it applies to science, encompasses the apprehension of quality and value in scientific statements, observations and methods. Michael Polanyi describes the operation of a scientific aesthetic as an intellectual passion and writes:

> The function which I attribute here to scientific passion is that of distinguishing between demonstrable facts which are of scientific interest, and those which are not. Only a tiny fraction of all knowable facts are of interest to scientists, and scientific passion serves as a guide in the assessment of what is higher and what of lesser interest; what is great in science, and what relatively slight. I want to show that this appreciation depends ultimately on a sense of intellectual beauty; that is an emotional response which can never be dispassionately defined, any more than we can dispassionately define the beauty of a work of art or the excellence of a noble action.(4)

The aesthetic mode of knowing in science is one which flows out of the student's own personal science. One cannot prescribe scientific beauty for the student. The student must, by dwelling in the ideas of science, become aesthetically aware of the science.

Although it is easy to find many examples that demonstrate the existence of an aesthetic within the personal science of creative scientists, is it really of importance to science educators and the vast majority of students who will not become scientists? The answer to this question is clearly yes, it is important to develop in students a sense of aesthetic awareness in science. Consider the following comment by Elliot Eisner:

> Pedagogical practices in American schools have become increasingly fragmented. Because of pressures upon teachers to become "accountable", there has been a widespread tendency to break curricula into small units of instruction. The result of this fragmentation is to make it increasingly difficult for students to see how each piece is a part of

> a larger whole. When the content taught for each small fragment is tested, the test is a signal to the student that he or she can forget what has been "learned" after the test has been taken. ... The educational liability of such teaching and learning procedures is that they emphasize short-term memory; it is difficult to remember small bits and pieces of information when there is no larger conception or armature upon which they can be placed. Indeed, this orientation to teaching and testing is formidable; it may make it difficult for students to achieve meaningful learning.
>
> ... If our educational program put a premium on the aesthetic as well as on the instrumental features of what is taught, students would have an opportunity to develop mental skills that for most students now lie fallow. Attention to the aesthetic aspects of the subjects taught would remind students that their ideas within subject areas, disciplines, and fields of study are human constructions, shaped by craft, employing technique, and mediated through some material. Works of science are, in this sense, also works of art.(5)

Another, no less direct plea for attention to the aesthetic mode comes in a comment made by Albert Einstein regarding education for independent thought:

> It is not enough to teach man a specialty. Through it he may become a kind of useful machine but not a harmoniously developed personality. It is essential that the student acquire an understanding of and a lively feeling for values. He must acquire a vivid sense of the beautiful and the morally good. Otherwise he - with his specialized knowledge - more closely resembles a well trained dog than a harmoniously developed person.(6)

As has already been noted, one acquires an aesthetic mode of knowing science by indwelling. The skilled scientist, through prolonged and intimate contact with his or her ideas has an "intuitive" or tacit level sense of beauty or value. The acquisition of this - largely ineffable - knowledge is often that which distinguishes the expert from the novice or from the second rate scientist(7) and may be (as noted earlier) what Holton refers to as the "themata-proneness of genius".(8)

The question which now arises, however, is how can one foster the development of such an aesthetic mode of understanding in science? This question is contained within the more general question - how do we encourage indwelling in the science curriculum?

4.3 The Use of the Narrative Mode in Communicating Personal Science

Eisner's aesthetic mode is subsumed under the more general idea of intellectual satisfaction. The extent to which a person indwells his or her science enables that person to respond in an aesthetic sense. This need not be the preserve of the accomplished scientist. A sense of the aesthetic would entail a sense of fullness, of coherence that places the science learned in school within the broader weave of the curriculum and ultimately the student's life beyond the walls of the school. In practical terms we require a pedagogy that strives for such an aesthetic within science education. Jerome Bruner provides us with a clue on how to achieve this.

In a recent essay, Bruner(9) maintains that there are two irreducible modes of thought; the paradigmatic and narrative modes. His ~~use of~~ the term 'mode' is more specific now than Eisner's usage of the aesthetic mode. Mode in Bruner's sense takes on a particular pedagogic orientation. The paradigmatic mode, as it applies to science education, is essentially the empiricist-rationalist position of traditional school science. In its essence, the paradigmatic mode is highly convergent and employs language in a consistent, non-contradictory manner. The "tools" of mathematics, logic and science are important components of the paradigmatic mode. As Bruner puts it:

> The imaginative application of the paradigmatic mode leads to good theory, tight analysis, logical proof, and empirical discovery guided by reasoned hypothesis.(10)

By contrast, the narrative mode is divergent and employs literary devices (metaphor, simile, hyperbole, etc) to evoke meaning as well as to explain. The narrative mode strives towards verisimilitude, to the creation of a plausible world of shared experience between the writer and the reader. Unlike the paradigmatic mode, good narrative may use obvious exaggeration, paradox, ambiguity or even contradiction to draw out meanings. The simple anecdote used at the beginning of this chapter is a case in point. A personal anecdote on the part of the teacher helped draw students into a shared world of experience in which the students could be reminded, perhaps, of resonances with their own experience. In this teacher's experience, the plausibility of rectilinear motion resulting when the constraints forcing circular motion were removed, was heightened for the students. This point has been made by Ronald Hyman(11), who suggests that in addition to providing "new insights and a rich base for comparison", stories or metaphors also serve a persuasive function. The fact that the teacher has experienced "tangential motion" helps persuade students of the plausibility of this idea and provides, if only vicariously, an episode in the memory of the student on which to "hang" this principle of kinematics. It should be added that the failure, on the part of students, to predict the motion of a projectile on leaving a state of circular motion is well documented in alternate conceptions research(12).

Michael Novak asserts that good teaching is directed towards the imagination and experience of students when he writes that:

> Thus, pedagogically, good teachers aim directly at the experience, imagination, stories of their students. Only in that matrix can understandings occur. The teacher tries to surprise students, explode their too limited patterns of expectation, raise the counterexamples that direct their attention in new ways. Good education is a constant series of new births: new ways of experiencing, perceiving, imagining, proceeding.(13)

Through the use of story we may lead our students to see that indeed they too have their own stories about science. Their personal experiencing of the world, recollected and shaped through the narrative mode, anchors the concepts we would have our students learn, in their own experiencing of the world.

The attractiveness of the narrative mode as a vehicle for communicating personal science and fostering indwelling is underscored by Bruner's comment that:

> Paradigmatic discourse, moreover, avoids all conversational implicatures if it can, and when it cannot, it employs only those that have heritage expressions that permit unambiguous unpacking of utterances back to the canonical or maxim-governed forms. **In logic and in science you attempt to mean what you say. In narrative, to be successful, you mean more than you say and treat text or utterance as open to interpretation rather than literally fixed with, so to speak, "truth in the text"**(14) [emphasis mine].

In Chapter 2 it was argued that an authentic portrayal of science attends to the richness inherent in science with special attention accorded the personal dimension of science. Here we find that the notion of richness also extends to the modes of thought employed by our students. For much of the intent of the science curriculum, the paradigmatic mode is a powerful and necessary way in which the student is to encounter science. But it cannot be the sole mode of thought employed. If we are to seriously address the problem of having students acquire a more authentic understanding of science in its diversity then the narrative mode must also become part of the intellectual approach used by science students and teachers.

4.4 Areas in Which the Narrative Mode May Prove Most Effective in the Teaching of Science

The growth of our personal science is contingent on the growth of our experience and on inculcation. While a great deal of scientific training must occur through Bruner's paradigmatic mode and the student's own grappling with and dwelling in formal ideas of traditional "school science", not all of science can be communicated and learned in this way. Through the narrative mode we can, by sharing in the ideas of a community, begin to dwell in those ideas.

In Chapter two nine aspects of science were explored with the suggestion that, in portraying science authentically, attention should be given to these areas. As well, it has been suggested that acquiring an understanding of these diverse facets of science requires that the student must dwell in them; the student's personal science must draw connections to these other aspects. In what way can the use of narrative add to the student's grasp of these dimensions? To answer this we will consider how narrative can be used to illuminate each of these aspects of science.

4.4.1 Methodologic Aspects

The acquisition of the correct methods of science and the mastery of technique are best approached through the highly focused paradigmatic mode of thinking. A student must learn the appropriate laboratory and mathematical skills by traditional methods of lab and problem solving activities. This does not mean, however that the use of narrative cannot illuminate certain aspects of the scientific methodologies. A case in point is James Watson's(15) The Double Helix. Written by one of the co-discoverers of the structure of DNA, this book is a fascinating glimpse into the actual practice of scientific research. The student is given a glimpse into a world of science open to very few and, through this shared experience, may gain a richer understanding of the way in which research occurs.

4.4.2 Epistemological Considerations

Narrative may prove particularly useful as a vehicle for exploring the epistemological dimension of science. A problem with the formal, expository delivery of philosophy of science topics is that it presupposes that the student already holds considerable knowledge of science and philosophy. Yet the kernel of many of the ideas about the epistemology of science can be communicated - at least tacitly - through story and anecdote. The Italian writer Italo Calvino has provided some fascinating and powerful examples of such writing in Mr. Palomar.

In this work we encounter Mr. Palomar, a passionate observer of nature and follow him in his search for knowledge and wisdom. Mr. Palomar consists of a collection of 27 short episodes, arranged in triads and each less than 5 pages in length. A common theme woven through these stories is the limitation that human language and powers of observation impose on our understanding. In the story "The Infinite Lawn"(16) Mr. Palomar faces the problem of deciding how to partition off exactly one square meter of lawn so that he can rid the lawn of any trace of dandelion or other interlopers. What he enters into instead is a potentially endless regression of reductionistic attempts at "seeing the lawn". No matter how he lays out the boundary there seem to be blades of grass that do not belong to either side of the partition. His musings at this point will be familiar to anyone acquainted with the Mandelbrot sets of fractal geometry in mathematics. Eventually Palomar begins to question his conception of "lawn". By lawn do we mean an integrated whole or a mathematical collection of discrete blades of grass? Mr. Palomar - a man not remarkable for his powers of uninterrupted concentration - loses his train of thought and:

> no longer thinks of the lawn: He thinks of the universe. He is trying to apply to the universe everything he has thought about the lawn. The universe as regular and ordered cosmos or as chaotic proliferation. The universe perhaps finite but countless, unstable within its borders, which discloses other universes within itself. The universe, collection of celestial bodies, nebulas, fine dust, force fields, intersections of fields, collections of collections ... (17)

Calvino, with a very simple and delightful character in the person of Mr. Palomar, challenges us to face the limitations of knowing imposed by our language and methods of observation. In so doing, he provides an engaging and accessible preface to a more formal presentation of epistemology of science or an informal "reminder" of this dimension of science.

Another writer who illuminates the epistemology of science is Loren Eiseley. In the story "The Hidden Teacher"(18) Eiseley recounts that while trekking through a gully in the Southwestern U.S. desert, he happened upon a yellow orb spider. After watching the spider for a few minutes, he plucked the spider's web with the tip of his pencil. The intrusion of the pencil tip was unlike any the spider had ever before encountered. In Eiseley's words:

> A pencil point was an intrusion into this universe for which no precedent existed. Spider was circumscribed by spider ideas; its universe was spider universe. All outside was irrational, extraneous, at best raw material for spider. As I proceeded on my way along the gully, like a vast impossible shadow, I realized that in the world of spider I did not exist.(19)

As Eiseley proceeded on his journey the image of the spider haunted him. He began to see that humankind is confined to a web of ideas as surely as the spider is bodily confined by its web. His story speaks eloquently of the power and the weakness of science. Such a story could be used to frame for the student questions concerning the nature and limitations of scientific knowledge. It could, for example, provide the student with an introduction to Kuhn's subtle idea of the paradigm. Just as the web is to the spider, so the paradigm is our web - a place to indwell. It provides us with intellectual support and allows us to frame theories and conjectures. Just as the spider's web does to the spider, it also confines us and limits these same ideas.

4.4.3 Personal and Private Science

Michael Polanyi stressed that "connoisseurship, like skill, can only be communicated by example, not precept."(20) In the previous examples, the role of narrative in communicating aspects of science was put in the context of the personal science of the student reaching out to establish meaningful connection with those other areas of science. All knowledge, in Polanyi's terms, is founded in a personal knowing. We have also used the term "personal science" to distinguish the aesthetic and motivational aspects of science - as they apply to individuals - from other dimensions of science (methodological, historical, etc.). Narrative can serve to share with others the personal enjoyment and motivations one has in science. This can be especially useful when a well known scientist, through autobiographical account, opens his or her world to the reader. An excellent example of this is found in the television documentary "The Last Journey of a Genius"(21), a fascinating glimpse into the life of Richard Feynman, one of the greatest of American physicists. In this documentary, made shortly before his death, Feynman shares many of the personal reasons for his being a physicist as well as his insatiable curiosity and desire to find answers. Instead of a lengthy discussion of his numerous (and esoteric) contributions to physics the documentary focuses on Feynman's attempt to visit the land of Tuva, an obscure state in central Russia that has been closed to the west since the time of Stalin. What unfolds is a sustained metaphor for the adventure of science as a trip to an unknown or exotic land.

Narratives emerging from the lived experience of others can function as a medium through which a student may share in the personal science of a teacher or perhaps an eminent scientist. Narrative can also perform an autobiographical or reflective purpose for the student. The use of journals and expressive writing in science and mathematics education has been well documented. Driver(22) et al. suggest that narrative could be be used to aid students in explicitly formulating their own ideas thereby exposing the contrast between their own perceptions and the formal conceptions offered by the teacher. Goodkin(23) and Watson(24) have shown that journal writing aids student visualization and successful solution of mathematical problems. Marilyn Frankenstein(25) has suggested the use of journal writing in the mathematics class as a way of reducing "math anxiety" and building positive intellectual self-image and it would seem reasonable to expect that this would hold for science class as well.

The idea of having students develop, through the use of stories, a sense of "ownership" and participation in the ideas of science has been suggested by K. Martin and E. Miller(26). In an example related in their paper, a group of elementary school children (seven and eight year olds) were arguing about the number of moons of Mars. Rather than tell them the right number, one of the authors told the story about the Roman god of war Mars, and his two loyal sons , Deimos and Phobos. The story removed all doubt about the number of moons of Mars. The story illustrates how culture and science were intertwined in earlier times. Martin and Miller conclude their paper with:

> The science books adopted in most schools transmit a body of knowledge with little attention to the bodies for whom that knowledge is intended. The very nature of such texts is unscientific. ... These texts offer children no stories, no connections between forms and forces, between observers and observed. Without this profound connectivity which is the lifeblood of science, the body of scientific knowledge can be reduced to a corpse. Through a storytelling [narrative] mode, scientific knowledge can be kept alive for children.(27)

4.4.4 Public Science

Public statements of science are declaratory in nature, either as they appear in text books or in research papers. Clarity of meaning and convergence of ideas is of primary importance in statements of public science. As such, the paradigmatic mode is the mode best suited to this aspect of science. Pines and West(28), for example point out that one of the central objectives of constructivist models of science education is to understand how students acquire large bodies of public scientific knowledge. Their research (as well as many others) suggests that the paradigmatic mode, as the sole mode of knowing, does not adequately achieve this objective. As we have seen, anecdotes can serve a function in the communication of public science by helping to root the public science within the student's personal science.

4.4.5 Historical Science

Michael Novak(29) has suggested that, unlike the humanities in which the person inquiring is of highest importance to the inquiry, the "who" in science is replaceable without loss. Most textbook portrayals of science unfold in an essentially contextless fashion. Historical detail, if present, consists only of a sprinkling of the names of great scientists with no attempt to relate the personalities and personal histories of these people to their discoveries. Working from within the empiricist-rationalist epistemology of traditional school science, the student encounters science as an objective, rational process which seems to overwhelm the student with a claim of authority and truth.

Philosophers and historians of science such as Thomas Kuhn(30), Gerald Holton(31) and Stephen Brush(32) have argued convincingly that the personal intellectual struggles scientists undergo to identify and solve important scientific problems are an essential part of the scientific inquiry. Familiarity with the personal struggles of earlier scientists can help students feel part of a timeless cultural community of inquirers, all of whom at times had struggles and doubts similar to those faced by many students.

The role of the history of science in teaching students about the limitations and nature of science and the tentative nature of scientific knowledge has been well reviewed in a number of publications (Brouwer and Singh(33) for example). Driver(34), Guesne and Tiberghien, Wandersee(35) and others have shown that student alternate conceptions are often very similar to ideas held by scientists at particular points in the history of ideas. In this respect, history of science may provide a vehicle for allowing students to explore their own conceptions and to see that others (the "community of scientists" - both past and present) at one time held similar conceptions but have now adopted different conceptions.

While a superficial treatment of the historical dimension of science may be achieved through the paradigmatic mode, the narrative mode provides an effective way of capturing the passions and struggles of scientists. As an example of this, consider the story told by Werner Heisenberg(36) of a conversation he had with an unhappy Albert Einstein on the way home from a seminar given by the young Heisenberg in 1926. Einstein was very upset by the implications of the new quantum theory:

> "What you have told us sounds extremely strange. You assume the existence of the electrons inside the atom, and are probably quite right to do so. But you refuse to consider the reality of their orbits, even though we can observe their tracks in a cloud chamber. [Einstein is here referring to the idea in orthodox quantum theory that it makes no sense to ascribe reality to the notion of a trajectory (and hence an orbit) for a particle.]

Later, when talking about the emission of light from atoms Einstein asked:

> "But what happens **during** the emission of light ... Can you not describe the transition (of the atom) from one stationary state to another more precisely?"

The story of Einstein's struggle with the probabilistic implications of quantum mechanics would have been comforting to those of us who also had difficulties with the implications of quantum mechanics when we were first exposed to them. Instead, it was often assumed that it was our own intellectual limitations that stood between us and the strange ideas of quantum mechanics. Even though our unfamiliarity with the similar struggles of Einstein, Schrodinger and others to accept the ideas of quantum mechanics probably did not hurt our ability to solve problems involving quantum mechanical techniques it did prevent us from seeing the great intellectual adventure quantum mechanics really was for its developers (and is for the student today).

Heisenberg's story about Einstein suggests that the learning of science is more than a rational, objective or empirical enterprise. Teaching science from a purely rational perspective connotes a sense of certainty, proof - even authority. Anecdotes can help temper this view with the illustration of doubt, uncertainty and intellectual struggle that are part of the development of science. Moreover, stories like this one help to draw young students, their teacher and their famous predecessors into a community of people interested in similar problems and often plagued by identical doubts. In so doing we are led to what Polanyi described as a "Society of Explorers" - a point to which we will return in chapter 7.

Stories or anecdotes have the potential for encapsulating the fundamentally important things in the life a scientist. Biographies can also fit naturally into the portrayal of this facet of science. An excellent example of this is Banesh Hoffmann's Albert Einstein: Creator & Rebel(37). Through this use of the narrative mode as it applies to the history of science, the student sees that eminent scientists like Einstein, Schrodinger, Heisenberg (and others) were not interested only in solving problems but had an overwhelming desire to understand what reality was all about, what laws of nature lay beneath the regularities that could be measured in the laboratories and described by mathematical equations.

4.4.6 Societal and Technological Science and the Aims of Science

A popular college chemistry text(38) opens one of its chapters with a colour photograph of a ruptured gas storage tank from which a huge plume of flame and smoke is billowing. In the background one sees that the event is occurring in a densely populated urban area. The caption to the photograph reads "an example of an exothermic reaction". In many chemistry texts the Haber process of ammonia synthesis is discussed with some indication of the personal details of Fritz Haber's life and Nobel prize. Seldom, however, is it added that the Haber process was largely motivated by military interests prior to the first world war. The failure to root science within a cultural, societal and technological matrix is a well documented problem in science education.

In many cases, simple expository means could address omissions such as those given above. A variety of STS issues could be introduced by using the examples of Linus Pauling, Albert Einstein, Robert Oppenheimer, Edward Teller, Francis Crick and numerous less famous scientists, in order to help students place STS issues in a human context. The narrative mode, however, could be used to illustrate in more subtle ways the relationship between science and society. Fictional portrayals of scientists in ambiguous societal situations can also be used to provide a context for STS discussions.

Brouwer(39) has explored the image of the scientist in modern drama. Through the eyes of a playwright, many of the tensions between the values of science and scientists and those of society can be explored. Henrik Ibsen, for example, explores the problem of responsibility and accountability in An Enemy of the People(40). Dr. Stockman, on discovering that the public baths which provide his Norwegian community its economic lifeblood are polluted and dangerous to the health of its patrons, faces the dilemma of alerting the community and risking economic loss or remaining silent. Although this play was written over a century ago its topic is very current today. William Golding's The Brass Butterfly(41) explores the problem of technological innovation and its impact on the Roman society. At the end of the play Caesar rejects the introduction of new technology into Roman society and concludes:

> A steamship, or anything powerful, in the hands of a man ... is like a sharp knife in the hands of a child. There is nothing wrong with the knife. There is nothing wrong with the steamship. The trouble is his [man's] nature.(42)

Friedrich Durrenmatt(43) explores the impact of militarism on science and technology in the play The Physicists. In the setting of an insane asylum, Durrenmatt discusses at least four choices scientists can make with regard to the destructive potential of their scientific research. One physicist chooses to accept military funding claiming that the ultimate responsibility for the application of his research lays with the military or political leaders. A second physicist decides to abrogate his responsibility to a political party which best represents his political beliefs. The third physicist, and central character of the play, chooses to withdraw from society and continue his research in isolation and safe from the possible destructive application of his discoveries. A fourth physicist represents the use of scientific knowledge for personal aggrandizement. In this play Durrenmatt illustrates the many subtle undercurrents that link science, society and technology and which reflect the culture in which we live and frame our values.

There are other examples of ways in which modern dramatists and writers have drawn into focus STS issues. Through the evocative power of the narrative mode, complex issues can be introduced that help root the student's perception of science within a much broader cultural context. In so doing, science educators may have reason to hope that students will begin to see the subtle ways in which science and culture are intertwined. Rather than just passing rational, objective "truth" to our students we should pass on to them something from our own experience of science which has been tempered by a warning given by Richard Feynman to:

> ... pass it [our experience] on with a delicate balance of respect and disrespect, so that the race does not inflict its errors too rigidly on its youth, but it does pass on the accumulated wisdom, plus the wisdom that it may not be wisdom.(44)

4.5 Conclusions

Science, in all its richness, engages us in both our paradigmatic and narrative capacities and any portrayal of science that strives to capture this sense of richness must, at some points at least, make use of stories, narratives or anecdotes. Stories and anecdotes open up the possibility of involving the imagination of students and in many instances evoke a response and demand participation from students(45). Often the students themselves are involved in giving meaning to the stories, and such stories resonate with the lives of individual students in personal ways.

Through the narrative mode of knowing, students can acquire from the history of science a sense of the doubts, struggles and triumphs of scientists. This will also emphasize that science is not strictly rational, neutral and objective but that the inquiring individual is an integral part of inquiry. While the paradigmatic mode of knowing has a legitimate place in science education, unchecked it often connotes a distorted notion of authority, proof or certainty in science. Stories help to draw out the divergent, non-rational and human current within science.

A number of the stories related above help to bridge the gap between the student's school learning and experience. They emphasize what is really important in the science we learn in school by tying it to the reality outside the school room. Stories also tend to draw together the storyteller, usually the teacher, and the listener, the student, and help to unite them both into a common learning community.

Some of the personal or intuitive components of the diverse aspects of science are difficult to relate in a logically didactic fashion but can be hinted at through the careful use of stories and anecdotes. Many of the tacit level antecedents to ideas can be cultivated through stories and in some cases a story helps us to know more deeply some things we may have been aware of before.

In some ways, stories and the narrative mode offer a more subtle pedagogy which is essential to science also. Stories convince, not by the brute force of logical reasoning, but by evoking images, by creating empathy between the listener and the story. Physics students better understood circular motion when the teacher's story persuaded them of the reality of tangential motion after release. In fact, such stories underscore the fact that, logical positivism not withstanding, science is, in essence, metaphoric(46,47); that scientists understand by drawing analogies from real life experiences--even in the most esoteric regions of science. As science teachers we need to exploit the imaginative, persuasive functions of such metaphors, or stories, to a greater degree and in such ways also increase the participation of our students in the learning process.

In Chapter 6, my stories of astronomy appear. Some of them are mere anecdotes but collectively they represent an attempt to share with the reader my own sense of personal science. Such stories provide the opportunity of demonstrating to my students the importance of the ideas of science within my life as well as introducing insights and engendering discussions on the scientific enterprise. Chapter 5 provides an overview of the astronomical research in which I am engaged and will form the context for the narratives given in Chapter 6.

Notes Chapter Four

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3. quotation taken from Gerald Holton and Stephen Brush, Introduction to Concepts and Theories in Physical Science (2nd ed.) p. 193.grasp.(3)
4. Michael Polanyi, Personal Knowledge, p. 135.
5. Elliot Eisner, Learning and Teaching the Ways of Knowing, p.34.
6. Albert Einstein. Ideas and Opinions. New York: Dell Publishing, 1973, pp. 73-74. The comment originally appeared in an article by Einstein regarding education for independent thought that appeared in the New York Times, October 5, 1952.
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10. Bruner, p. 98.
11. Ronald Hyman. Ways of Teaching (2nd ed.), 1974, p. 34.
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13. Michael Novak. Ascent of the Mountain Flight of the Dove: An Invitation to Religious Studies. p. 57.
14. Bruner, p. 109.
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Chapter Five
Astronomical Investigations

5.1 Introduction

What follows is a description of three investigations that have occupied me for much of the past three years. Two of these projects (the study of the ellipsoidal variable star 42 Persei and an international project on Delta Scuti stars) are ongoing while the third project (a search for rapid oscillations in A type stars) has been, for the present, abandoned. A more technical discussion of these projects is given in Part B, chapters 8,9 and 10 of the thesis. It is these investigations that have provided some of the insights into personal science developed in this thesis and described in narrative form in the next chapter.

5.2 My Research Within the Broader Scope of Modern Astronomy

The past two decades of astronomical research have witnessed a remarkable proliferation of ideas including such exotic topics as black holes, quasars, dark matter and exploding galaxies. Despite the burgeoning scope of modern astronomy, it is our knowledge of the structure and evolution of stars that remains as the central, unifying thread that weaves astronomy into its present form. Even though the modern theory of stellar evolution ranks as as noble and profound an achievement as any in science, our knowledge of the basic properties of stars - their masses, sizes, compositions and internal structures - is far from complete. The research in which I engage falls within the realm of fundamental stellar astronomy. Through the analysis of close binary stars or oscillating δ-Scuti and peculiar A stars I hope to elicit some of the basic properties of stars.

5.3 Some Basic Ideas About Stars

The idea of what a star is, is probably the most basic notion in astronomy. The concept of star is as fundamental to astronomy as the idea of cell is to biology. In simple terms, a star is a gravitationally bound, self luminous gas sphere. Stars can vary in mass from a few tenths the mass of our sun to perhaps as much as 100 times the solar mass. The radii of stars can be as little as 10 km or less for neutron stars to larger than the orbital radius of the planet Mars in the case of a bloated red giant star like Betelgeuse - the bright red star in Orion. Surface temperatures of stars are measured in the thousands to tens of thousands of degrees kelvin, while the central temperatures are measured in millions of degrees kelvin.

A glance into a dark sky crowded with stars will reveal a bewildering diversity of brightness, color and pattern. Bringing order to this diversity stands as one of the crowning achievements of astronomy in the early part of this century. In 1912 Ejnar Hertzsprung and independently, Henry Norris Russell, discovered a pattern that relates the intrinsic brightness or **luminosity** of a star (ie., corrected for its distance away from us) to its surface temperature. Today this pattern is known as the Hertzsprung-Russelll (or HR) diagram and is as significant a pattern for modern astronomy as the hydrogen spectrum is for atomic physics, the Krebs cycle for biology or the Rosetta stone for Egyptology.

Figure 5.1 shows a common version of the HR diagram. Along the bottom axis of the diagram is shown surface temperature as well as a letter code called the **spectral sequence.** The vertical scale is measured in units of luminosity relative to the sun. The significance of the HR diagram lies in the pattern that emerges when one plots a star's surface temperature and luminosity. The gentle curve weaving through the middle of the diagram is called the **main sequence.**

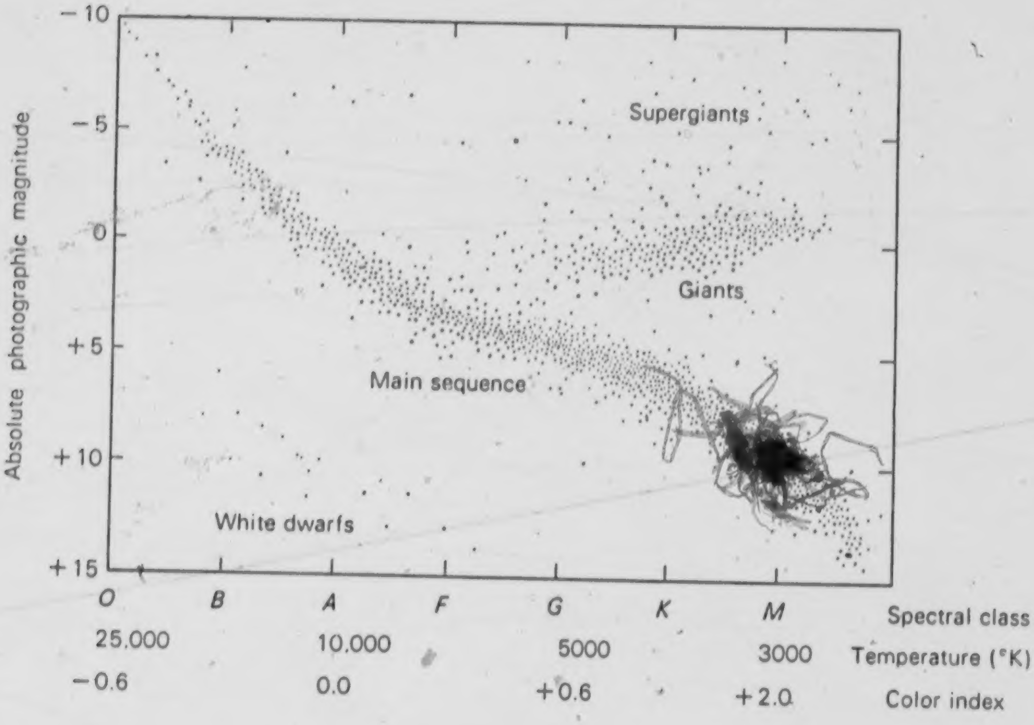

Figure 5.1 The Hertzsprung-Russel diagram which, among other things, shows the relation between stellar luminosity and temperature.

According to stellar evolutionary theory, a star forms by condensing from a diffuse dust cloud to form a luminous star. On the HR diagram young (ie. recently formed) stars lie along the main sequence. As a star ages, re-adjustments of its temperature and radius cause the luminosity-temperature relationship for that star to change. This is reflected in the HR diagram by a change in position with respect to the main sequence line. A star will "move" up and to the right of the main sequence and then almost vertically onto what is called the **red giant branch**. As evolutionary change continues, the star will move again, this time almost directly across and to the left on the HR diagram. By carefully determining a star's surface temperature and brightness one can determine its proper placement on the HR diagram. This allows one to infer a great deal about the evolutionary status of a star.

The bottom axis of the HR diagram is also labeled with a letter and number code called the **spectral sequence**. The sequence, in order of **decreasing** surface temperature is: **O,B,A,F,G,K,M**. Stars are usually identified by assigning them a spectral type. This immediately places the star on the HR diagram. In the research to be described below most of the stars discussed are A-type stars. This indicates that they have surface temperatures on the order of 10 000 K and are about 10 to 100 times as luminous as the sun.

In addition to the main sequence line on the HR diagram there are five other locii providing meaningful categories with which to describe stars on the basis of their size and intrinsic brightness. These categories are known as **luminosity classes**, and range, in increasing order of stellar size, from the main sequence through type Ia supergiant stars. Figure 5.2 shows the HR diagram and the six luminosity classes denoted by Roman numerals.

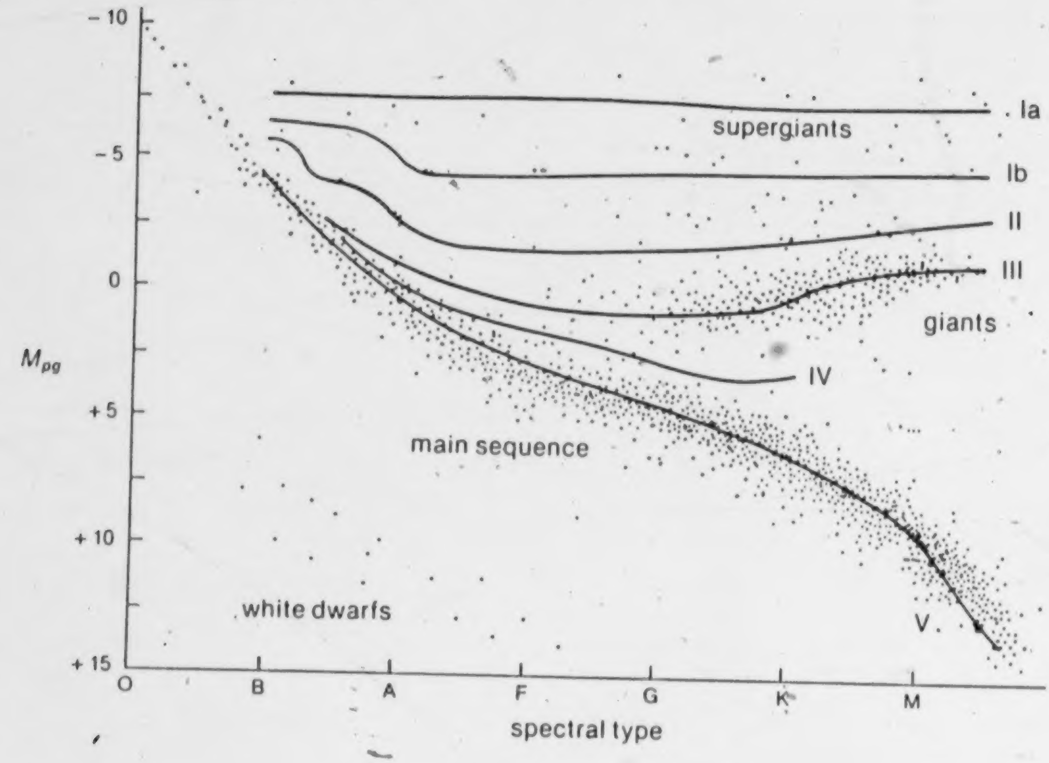

Figure 5.2 The luminosity classes lying on the Hertzsprung-Russel diagram

When classifying a star it is normal to specify both its spectral type and luminosity class. Our sun, for example is a G2 V star. This indicates that it is a small, main sequence star with a surface temperature of about 5800 K. Most of the stars described in this thesis are main sequence stars of spectral type A or F.

5.4 Astronomical Photometry

A chemist has a laboratory stocked with reagents and assorted chemicals, a paleontologist may have a twisted heap of petrified bones while the biologist has an entire world teeming with countless plants and animals. I have only a few feeble rays of starlight from which to tease out the secrets of the stars. Across the frozen and timeless gulf of space this feeble trickle of photons carries, encoded within, information about the brightness, composition and temperature of the stars. By dispersing the light in a spectrograph I can infer something about the motion of a star, its composition, temperature and possibly the presence of a companion sun. The analysis of stellar spectra falls under the heading of **stellar spectroscopy** and represents one of the major branches of observational astronomy.

As well as investigating the color of the starlight I can painstakingly measure the **amount** of light that I receive each second from the star. This form of "cosmic accounting" is known as **photometry** and is the proper setting for my type of research. By carefully measuring the amount of light or **flux** from a star in several different wavelength regions one can gain insight into the temperature, size and type of that star. It is by noting any variations in the brightness of the star that the shape of the star, the presence of a companion, and possibly the dimensions of the star or stars may be inferred.

The science of astronomical photometry is as old as observation itself. The human eye is a splendid example of a light detector able to operate over an immense range of brightness. More than 2000 years ago the Greek astronomer Hipparcus devised the first photometric system - the magnitude scale for describing the brightness of the stars. In its original form, the brightest stars were assigned a magnitude of 1 while the faintest visible stars were given a magnitude of 6. This scheme was later modified by Claudius Ptolemy in 180 A.D. to accommodate the few stars brighter than first magnitude but the basic scale was retained. In 1856 (acting on an earlier suggestion of Herschel's) N.R. Pogson suggested that a first magnitude star was 100 times brighter than a sixth magnitude star. This leads to the result that a star which is 1 magnitude unit brighter than another star is 2.512 times as bright as the fainter star.

While the human eye is capable of operating over an immense range of brightness, it is not particularly sensitive to small differences in brightness. In practice, a skilled observer can detect brightness differences as small as 0.2 magnitude units. For a large number of astronomical objects, and especially the ones described in this thesis, a 0.2 magnitude variation is huge - roughly 50 times greater than the precision I require in my measurements. To permit the measurement of subtle variations in stellar brightness I use a **photoelectric photometer**.

In this device, starlight is focused on the face of a vacuum tube containing a surface which ejects electrons when illuminated. When a photon strikes the emissive surface an electron is ejected and accelerated toward the other end of the tube. On the way the electron collides with properly placed surfaces inside the tube causing the ejection of additional electrons. This process is called **cascading** and means that a single electron emitted at the front of the tube will emerge with a swarm of up to a million attendant electrons. The result is a brief but measurable electrical pulse that can be recorded and used to signify the arrival of a photon of light at the photometer. Thus, the brightness of a star may be quantified as the number of photons detected by the photometer in a given period of time. While a photoelectric photometer cannot operate over as large a range as can the human eye it is very sensitive to small variations in brightness.

5.5 Differential Photometry

While the basic idea of photometry is simple there are many practical problems associated with measuring the brightness of a star. The most serious difficulty has to do with the obscuration of the star by the Earth's atmosphere. As well, subtle instrumental effects must be accounted for if one is to acquire meaningful observations. The appraisal of these problems and any observations secured calls upon the astronomer's judgment, experience and ingenuity.

One of the most common methods used to minimize the effect of the Earth's atmosphere on photometric observations is the technique of **differential photometry.** In this method the brightness of one star is compared with the brightness of one or more nearby stars of similar brightness and color. Assuming that at least one of these comparison stars is constant in its brightness one can then detect variations in brightness in another star by monitoring the difference in the brightness of the two stars. As long as the stars are close together in the sky (usually within a degree or two) effects due to changes in the Earth's atmosphere will be minimized. Under good conditions one is able to measure relative brightness changes on the order of several thousandths of a magnitude by employing this technique.

5.6 Photometric Systems

No two telescope and photometer systems are identical. Each has its own peculiarities and comparing observations made at two observatories with two different photometers is not a trivial process. To make the sharing of data between different observatories possible the astronomical community has established specific conventions or photometric systems. The most widely used photometric system is the **UBV system** and is the system used in this thesis.

The UBV system is based upon observations made in three broad spectral regions through specially designed filters designated U, B and V. Each filter transmits a spectral band approximately 90 nm wide with the U filter centered at 350 nm (near ultraviolet), the B filter centered at 430 nm (blue) and the V filter centered at 550 nm (visible). By monitoring the light emitted by a star in these three spectral regions it is possible to form a crude idea of that star's temperature, age and composition.

Crucial to the UBV system (and any other photometric system) is a series of **standard stars**. Nearly forty years ago Johnson and Morgan(1) and Johnson and Harris(2) published a list of 108 stars that had been extensively observed Ten of these stars serve as the primary standards for the entire UBV system with the remainder serving as additional standards. As well as these stars, several hundred stars in the Pleiades, Praesepe and IC 4665 star clusters were observed and act as a set of UBV cluster standards(3). All observations made world wide ultimately are compared to the observations made by Johnson et al. on their particular photometer. An important task of any astronomer using the UBV system is to carefully calibrate his or her equipment with respect to this standard system. The calibration of the Devon photometer is described in chapter 8 of this thesis.

5.7 The Ellipsoidal Variable 42 Persei - A Close Binary Star

Approximately one half of the stars we see are members of binary or multiple star systems. This is a fortunate state of affairs for it is by studying the properties of binary star systems that one is able to infer a great deal about the physical properties of stars in general. This point was recognized over two centuries ago by Sir William Herschel who wrote:

> The wonderful train of consequences that can be drawn from such regular occultations [of Algol] should engage our utmost attention(4)

One of my current research areas is the study of a subset of binary star systems known as the **ellipsoidal variable stars** and one member of this class in particular - the star 42 Persei. The following discussion concerns observations carried out over approximately one and a half years and provides the first reliable light curve for this system as well as confirming an earlier suspicion (Batten(5),1987) that 42 Persei is a member of the ellipsoidal class of variable stars.

One of the first suggestions that some of the stars we see are actually members of binary systems was made in 1782 by John Goodricke. Although, nearly a century earlier the Italian astronomer Montanari had noticed that the bright star Algol, in the constellation Perseus, was variable in brightness it remained for Goodricke to demonstrate that the brightness variation of Algol was periodic and to measure the period. Goodricke's published period for Algol was very close to the currently accepted period of 2.8673075 days. Goodricke made the bold suggestion that the variation of Algol's brightness was due to the eclipse of Algol by a darker companion. A large number of binary star systems can be resolved telescopically and appear as a pair of stars. Over the course of many years the relative motion of these stars can be measured and from this a great deal of useful information can be inferred. The majority of binary systems, however, are either so far away from us or so close to each other that they cannot be resolved. It is only by noting variations in the brightness of the star system or periodic changes in the positions of spectral lines that can one discern the binary nature of such systems.

Photometric observations of a binary star system will often reveal information about the size, mass and configurations of the stars in the system. For some systems it becomes apparent upon analysis that the stars are so close together that large tidal distortions stretch the stars into ellipsoidal configurations. Such stars are classified as **close** binary systems with the **ellipsoidal** stars being a particular kind of close binary system. Figure 5.3 depicts a close binary system.

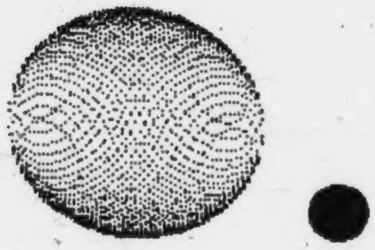

Figure 5.3 A close binary system. In this graphic, both stars orbit a common center and each is distorted by the gravitational pull of the other.

In this computer graphic it is apparent that the separation between the stars is only slightly greater than the dimensions of the stars themselves and that both stellar surfaces are distorted into ellipsoid-like shapes.

There are several factors that will contribute to the observed variability in the brightness of an ellipsoidal system. The first is the occurrence of eclipses. Whether we see an eclipse or not depends on the angle that the orbital plane of the system makes with our line of sight and on the relative dimensions of the stars and their orbital separation. For non-ellipsoidal systems (ie. well separated, non-distorted) this is the dominant cause of variability. A second reason for the variability of an ellipsoidal system arises from the distorted shape of one or both members of the pair. As the stars move in their orbit they will present to us a continuously varying surface area. Since the apparent brightness of a star depends on the surface area that we see, the result will be continuously varying brightness for the ellipsoidal system.

In addition to eclipse and distortion effects there are a number of more subtle phenomena that will contribute to the variation in the brightness of the system. The three most significant of these "secondary" effects are known as **gravity darkening, limb darkening**, and the **reflection effect**.

Gravity darkening arises from the fact that the brightness of a star depends on the effective surface gravity of the star. For a spherical star that is not rotating the surface flux is constant anywhere on the stellar surface. If the star rotates rapidly the surface gravity will be slightly less at the equator of the star than at its poles. This will mean that the star is darker at the equatorial region than at the poles. If the stars are elongated into ellipsoidal shapes, the surface gravity and hence brightness will be lower at the tips of the ellipsoids.

The effect of limb darkening is easily discernible on the surface of the sun as a gradual drop in brightness as you go from the center of the solar disk to the limb. The light that we see coming from the limb of the sun is shining obliquely through the solar atmosphere. This implies greater absorption and hence only light produced higher up in the solar atmosphere will escape from the solar atmosphere. Since it is cooler in the upper layers of the solar atmosphere the flux is correspondingly lower (ie. darker). This same effect will apply to all stars but the magnitude of the effect depends delicately on such factors as the size, temperature and composition of the star.

Another effect peculiar to close binary systems arises from the heating of one component by the other and the corresponding re-radiation of light. This is a very complex and poorly understood effect commonly referred to as the reflection effect.

The major effects of eclipse and ellipsoidal distortion as well as the secondary effects of reflection, gravity and limb darkening all conspire to make the analysis of the light variations in a close binary system fascinating as well as challenging.

5.8 Light Curves for 42 Persei

Figure 5.4 shows a graphical representation of the variation of brightness in the system 42 Persei in the U, B, and V wavelength regions. Such a representation is referred to as a **light curve**. The vertical axis shows the difference in brightness between 42 Persei and the constant star, HR 1164. Since the light output from the 42 Persei system is varying periodically it makes sense to measure this variation against a specific point or phase for the system. Hence the horizontal axis is measured in units of phase with a total of 1 phase unit corresponding to the repetition of one complete cycle in the system's optical variation.Figure 5.4 U,B, and V wavelength region light curves for 42 Persei.

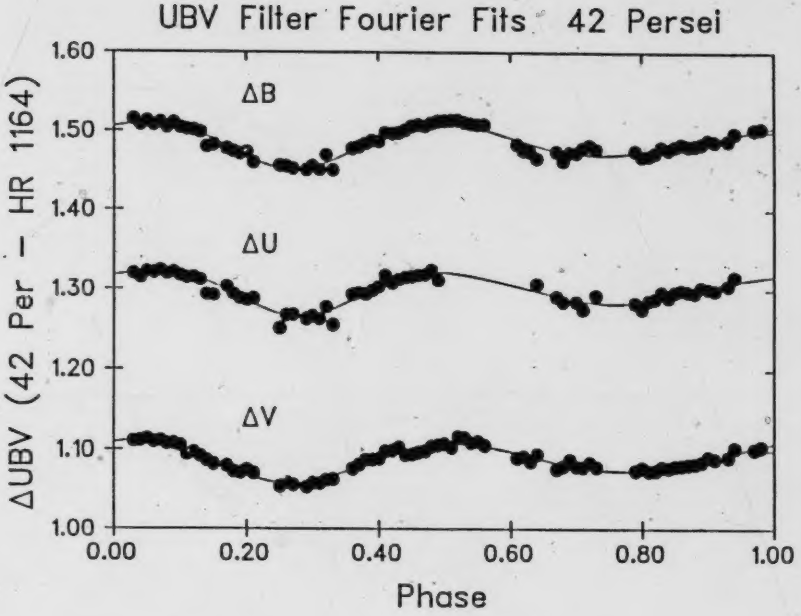

Figure 5.4 Photometric variation of 42 Persei in the U, B and V filter regions.

A light curve acts as a signature for a binary system. While it is not clear from looking at the curve for 42 Persei if an eclipse occurs it is evident that there is considerable ellipsoidal distortion in one or both components of the system. The signature for this effect is the continuously varying shape of the light curve resulting from the varying surface area of the stellar surfaces visible to us.

The reflection effect, if significant, will appear as an asymmetric brightness before and after the two minima that are visible on the light curve. There is no evidence of such an effect on the light curves for 42 Persei even though the obvious distortion of one or both of the components would suggest that they are very close together. A possible interpretation of this is that the cooler component of the system is much smaller in size than the other component and any reflection from this component would contribute very little to the total light of the system.

The limb and gravity darkening effects influence the light curve of a binary system in subtle ways and are not readily discernible. Their importance is inferred on the basis of models one constructs. Such models may be highly simplified "pencil and paper" models from which calculations can be carried out giving a predicted light curve for the system. The models can also be the product of highly sophisticated computer models. In either case, the astronomer, in forming an intuitive feel for the system, is guided by his or her visual inspection of the light curve. This is a practiced assessment of not only the statistical quality of the data but also an estimation of what are the most significant features on the light curve.

The ability to interpret and assess a light curve, like many skills in science, has both an articulated and tacit dimension. By working with a senior astronomer, through experience and by learning the techniques of one's discipline, one begins to acquire the connoisseur's eye and to bring to bear judgment on the analysis at hand. It is this inescapable personal element which prevents an experimental science such as astronomical photometry from becoming a merely mechanical act.

5.9 A Possible Model for 42 Persei

It is now known (and confirmed by the present research) that 42 Persei is a binary system with a period slightly longer than 1.765 days. Such a short period implies a very small orbital radius for the system. This hunch is bolstered by the shape of the light curve that has been constructed for the system. Spectroscopy indicates that one of the components is an A-type star and thus has a mass on the order of 2 times the solar mass. As well, spectra for the 42 Persei system show no evidence of the other star. This would suggest that the companion star is much fainter, cooler and almost certainly much smaller than the A-type component.

Following the work of Kopal(6) and Morris(7) and using the considerations given above, a simple analytic model for the 42 Persei star system has been constructed (the details of this model are given in chapter 8). Table 5.1 summarizes the major features of this simple model.

This analytic model has been used as the starting point for a more sophisticated computer analysis of the 42 Persei system. The Wilson-Devinney (WD hereafter) computer program has been used to construct a model for the system that provides us with an estimation of the sizes and shapes of the two stars as well as providing a synthetic light curve that we can compare to our actual observations. Table 5.2 shows the WD solution for 42 Persei while Figure 5.5 shows the comparison between the actual data and the predicted brightness of the ellipsoidal system. Underneath the light curve, at various phase values, a computer graphic shows what the model predicts the 42 Persei system would look like.

Possible solutions for various
Mass, mass ratio, inclination and mass function

M_1	q	i	M_2	F
1.900	0.190	72.0	0.361	0.0079
1.900	0.184	68.0	0.350	0.0067
1.900	0.187	70.5	0.355	0.0074
2.000	0.190	64.5	0.380	0.0071
2.000	0.191	65.3	0.382	0.0074
2.000	0.187	63.0	0.374	0.0066
2.100	0.195	62.0	0.409	0.0075
2.200	0.200	59.0	0.440	0.0077
2.200	0.198	58.4	0.436	0.0074
2.200	0.203	60.0	0.447	0.0083

"Best" solution:Parameters used:

			limb darkening	gravity darkening
M_1 =	2.0 (A3V)	U	0.41	1.02
M_2 =	0.38	B	0.54	0.87
q =	0.191	V	0.45	0.73
i =	65.3			
R =	3.48			
a =	8.207			

Table 5.1 Simple model, derived from Morris' approximations, for the close binary system 42 Persei

Wilson-Devinney LC Solution for 42 Persei

Element	average of V and B solutions
i	$65^\circ.3$
q	0.19
T_p	8800K
T_s	3500K
Ω_p	2.70 ± 0.05
Ω_s	4.00 ± 0.5
r_p: pole	0.40 ± 0.01
r_p: point	0.43 ± 0.01
r_p: side	0.41 ± 0.01
r_p: back	0.42 ± 0.01
r_s: pole	0.07 ± 0.02
r_s: point	0.07 ± 0.02
r_s: side	0.07 ± 0.02
r_s: back	0.07 ± 0.02

*all radii are expressed as percentages of separation between primary and secondary stars.

Table 5.2 Model for 42 Persei derived from application of the Wilson-Devinney modeling code.

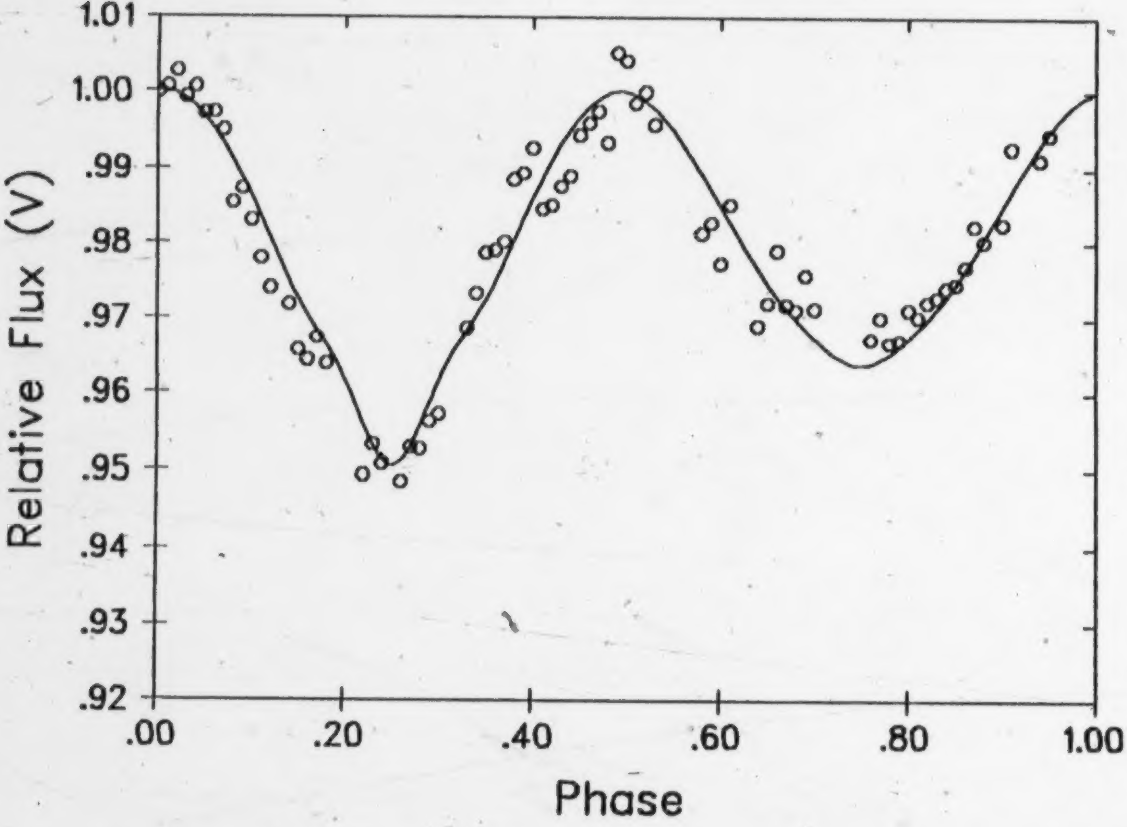

Figure 5.5 A comparison between the observed V filter light curve for 42 Persei and the one predicted by the WD modeling code.

Of particular note in both solutions is the very small mass of the secondary star in this system. The suggested mass of 0.5 solar masses would imply that the secondary is a mid M-type star. According to the theory of stellar evolution, the rate at which a star evolves depends roughly on the cube of the mass of the star. This fundamental fact poses an interesting problem for the solution suggested for 42 Persei. The problem becomes one of explaining how two stars of such dissimilar mass could form a binary system in which the bright component appears to be a normal, relatively young A-type star. In the time required for an M-type star to form, an A-type star should show evidence of aging. One way to detect this is to measure the relative brightness of the star in the U, B and V regions of the spectrum.

As a star ages the U-B and B-V magnitude differences should increase. The U-B and B-V values for 42 Persei are normal for a young A star. It is difficult to reconcile, on the face of it, the observed young A-type star with the implied M-type companion.

This anomaly presents an interesting challenge to the suggested solution for 42 Persei. Plans are now underway to try to detect the faint companion star. This will be done spectroscopically. An M-type star is cool enough that a large number of metallic element spectral lines should be visible in the far red - near infrared part of the spectrum. Since an A-type star will have a relatively "clean" spectrum in this region it may be possible to detect a faint M-type spectrum impressed on the brighter A-type spectrum.

5.10 The Significance of the Research on 42 Persei and the Question of Value

The present research brings to some degree of coherence a small "puzzle" begun 75 years earlier. In 1912 Adams(8) provided the first spectroscopic evidence that the system is binary. In 1978 Kolykhalova et al.(9) published a period of 22.58 days for this system. Their period was based on photometry but was in marked disagreement with a spectroscopic period of 1.765 days produced by Morbey and Brosterhus(10) in 1974. The observations and analysis reported here support the Morbey and Brosterhus result and provide the first successful model for the 42 Persei system. A natural question to ask of this research is what is its significance to astronomy and science in general?

Questions of the significance and relevance of fundamental research often require subtle answers. Is science enriched by this particular datum? Yes, but only by a very small amount. Is this research and its product characteristic of much of fundamental science? Most likely, yes.

It is the affirmation of this last question that deserves amplification. In Kuhnian terms the present research is an example of **normal science** (and hence in this respect characteristic of at least Kuhn's view of science). Using Kuhn's terms of reference, my research is an example of **puzzle solving**, and, as Kuhn puts it:

> Puzzles are, in the entirely standard meaning here employed, that special category of problems that can serve to test ingenuity or skill in solution. ... It is no criterion of goodness in a puzzle that its outcome be intrinsically interesting or important. On the contrary, the really pressing problems ... are often not puzzles at all, largely because they may not have any solution at all. ... Though intrinsic value is no criterion for a puzzle, the assured existence of a solution is.(11)

In the case of 42 Persei, the puzzle is one of piecing together spectroscopic and photometric data to provide a coherent picture that resolves some of the confusion regarding the correct period and nature of this object. This is a puzzle for which the possibility of solution seems highly probable.

Kuhn later asserts that:

> A man [or woman] may be attracted to science for all sorts of reasons. Among them are the desire to be useful, the excitement of exploring new territory, the hope of finding order, and the drive to test established knowledge. ... The scientific enterprise as a whole does from time to time prove useful, open up new territory, display order, and test long-accepted belief. Nevertheless, the **individual** engaged on a nor-

> mal research problem **is almost never doing any one of these things.** Once engaged, his motivation is of a rather different sort. What then challenges him is the conviction that, if only he is skillful enough, he will succeed in solving a puzzle that no one before has solved or solved so well. Many of the greatest scientific minds have devoted all of their professional attention to demanding puzzles of this sort. On most occasions any particular field of specialization offers nothing else to do, a fact that makes it no less fascinating to the proper sort of addict.(12)

Kuhn provides me with a way to justify my assertion that the research reported here has significance for astronomy. The successful resolution of a puzzle comes through the application of the established traditions of an identifiable body of knowledge. In this case the accumulated wisdom of stellar astronomy has provided the "rules" by which I have attempted to solve the 42 Persei puzzle. That a solution has been found, then, can be considered a success with respect to the research tradition in which my research is rooted.

Kuhn's characterization of normal science as puzzle solving provides a useful context in which to understand the research on 42 Persei. While I agree with Kuhn that it is the challenge of solving a puzzle that engages and motivates me and that there is a very real sense of satisfaction when the puzzle begins to resolve itself, this cannot be all there is to normal science. I would suggest that Kuhn is mistaken to conclude that the puzzle need not be intrinsically interesting or valuable. The appraisal of value is an essential and largely tacit skill that a student of science must acquire if he or she is to become a creative and productive member of the scientific community. Thus, my sense of intellectual satisfaction over puzzle solving is also attended by my recognition of value in the research that I do. Both the sense of satisfaction and appreciation of value in a scientific puzzle possess a strong personal coefficient. This points to the essential personal component of science that will be explored in the next chapter.

Polanyi(13) develops the idea of scientific value when he states that a result is valuable when it possesses, concurrently, three features: (1) certainty (accuracy), (2) systematic relevance and (3) intrinsic interest. These three factors will appear in varying degrees and depend on the specific research problem being considered. The recognition of value in science is a subtle and yet important attainment for any working scientist. As imprecise as the term is, the scientist is routinely asked to make assessments of the value of either his or her own work or the work of colleagues. Without a sense of what is valuable, the scientist is adrift, possibly wasting valuable time caught up in a "Pickwickian(14)" pursuit of trivialities. The reluctance of scientists to engage in explorations of topics such as ESP, UFO's, astrology or (rightly or wrongly) cold fusion are examples of topics that, for many scientists lack enough scientific value to make them worthwhile.

The present research on 42 Persei can be deemed valuable on all three of Polanyi's conditions. It satisfies the first two conditions in as much as it corroborates earlier observations (hence it possesses a measure of certainty) as well as extending stellar astronomical theory to the description of yet another problem (thus the research has systematic relevance). The research also possesses intrinsic interest in that the conclusions (the anomalously low mass of the unseen companion star) suggest another puzzle. Thus, the problem has proven fruitful. While clarifying one puzzle, the research has helped frame a potentially more interesting puzzle that may have implications stretching far beyond the original intent of the research.

5.11 The Study of Delta Scuti Variable Stars

Not all variable stars are members of binary or multiple star systems. For many stars the cause of variation arises from intrinsic factors related to the star's internal composition, size and temperature rather than from the eclipse or distortion of a nearby companion.

The first catalogued variable star was the deep red star Omicron Ceti, otherwise known as Mira and furnishes an example of what is termed an **intrinsic variable** star. This finding was made by the Dutch astronomer Holwarda in 1636. By 1784 Goodricke and Pigott had added, respectively, the bright stars Delta Cephei and Eta Aquilae to the list of known variable stars. Throughout the 18th and early 19th centuries the phenomenon of stellar variability was considered to be a very rare one. By the beginning of this century, however, and largely due to the advent of astronomical photography, the list of variable stars had grown to over 4000 listings. Today there are tens of thousands of known variable stars and it is clearly recognized that many of these variables are examples of pulsating stars.

The group of intrinsically variable stars is diverse and can be subdivided into many distinct kinds of pulsating stars. Delta Cephei and Eta Aquilae are bright yellow supergiant stars and are exemplars of the **δ Cepheid** variables - stars that pulsate with regular periods ranging between 1 and about 50 days. Mira is the prototype for the **Mira** variables - highly swollen red giant stars that vary in a semiregular manner with periods of several hundred days. Still other types of intrinsically variable stars include the RR Lyrae, Beat Cephied, Dwarf Cepheid and Delta Scuti variables. It is this last group of stars that will be described in the following sections.

The **Delta Scuti** (δ-Scuti) variables are a group of intrinsically pulsating stars of spectral types A and F and occupy a well defined region of the Hertzsprung-Russell diagram. They were recognized as a distinct class of variable star in the mid 1950's and today there are roughly 130 known δ-Scuti stars. The δ-Scuti variables are characterized by low amplitude light variations having periods of between 1 and 3 hours. The light variations for some δ-Scuti stars are often quite complicated in nature and suggest that there are many different periods of oscillation present.

It is the multiple periodicities present in the oscillations of some of the δ-Scuti stars that make them particularly interesting and important. Just as seismologists use the complicated vibrational patterns produced by earthquakes to probe the deep interior of the Earth, astronomers can use the complicated vibrations inferred from the light curves of δ-Scuti stars to "probe" deep inside a star. This is a very new area of astronomy, barely a decade old, and has been termed **astroseismology**.

5.12 The Cause of Stellar Pulsation

That an object as large as a star can pulsate in a regular fashion with a period of only an hour or so seems an extravagant idea. The reason for pulsation is intimately connected with the internal constitution of the star. That pulsating variables tend to occupy well delineated regions of the HR diagram provides an important clue to the cause of pulsation.

For a star to be a stable body the inward crush of gravity is balanced by the outward pressure exerted by the heated gases that make up the star. Radiant energy created deep inside the star slowly diffuses outward in a succession of absorptions and re-emissions. The stellar gas's tendency to absorb radiation is called **opacity**, and it is the opacity of the gas throughout the star that responsible for the supporting pressure in the star.

Imagine that the outer envelope of an otherwise stable star is compressed slightly (ie., given a slight boost in internal energy). Random motions occurring in the interior of a star will provide the small fluctuations needed to provide this compression. The compression will result in a heating of the envelope which will increase the amount of radiant energy emitted in that region. Usually the opacity of a gas will drop as it is compressed and heated. The envelope will quickly radiate away this additional energy and the envelope will bounce back to its original position. Although the envelope may overshoot its original position to produce a rarefaction and begin a back and forth oscillation, it will eventually return to its original position, having radiated into space the small additional amount of energy introduced by the compression.

Under these conditions stellar pulsation would be a short lived and much rarer event than observed. Since this is not the case, some mechanism must be at work to drive the pulsations in variable stars.

In particular, the opacity of the gas must increase under compression thereby extracting energy from the star. An increase in opacity would increase the pressure exerted by the gas and lead to expansion. As the gas expands outward the opacity would need to drop - the opposite of what "normally" happens. This would allow the energy originally trapped by the compression to be radiated away at a later time in the oscillatory cycle. The star would at this point be distended, and having lost the additional energy picked up on compression, would begin to collapse. This would lead to another compression, increased opacity and the cycle would repeat itself. Random perturbations inside the star would provide the energy needed to drive the pulsations on a sustained basis.

The mechanism just described is referred to as Eddington's valve to acknowledge the idea's originator - A.S. Eddington. It is now generally agreed that in the interior of stars there are specific regions in which the valve mechanism can operate. That is, there are regions in which the opacity of the gas will increase under compression and decrease under rarefaction. These regions are the hydrogen and helium ionization zones and are regions in which these elements change from one state of ionization to another. For driving stellar pulsation, the dominant ionization zone is the one in which singly ionized helium (HeII) is converted to its doubly ionized form (HeIII). When a compression occurs in the HeII-HeIII zone the temperature remains roughly constant since the energy that would otherwise increase the temperature is used in ionizing HeII. The increased density of compression leads to an increase in opacity which results in a local increase in pressure. The zone expands outward and as it does so the HeIII ions convert back to HeII. This slows the rate of cooling slightly and allows the opacity to drop thereby releasing the energy stored earlier in the cycle.

While all stars have hydrogen and helium transition zones it is only when the HeII-HeIII zone is located at the appropriate depth that it can sustain observable stellar pulsations. If the zone occurs too deep inside the star the overlying weight of stellar material is too great to allow the valve mechanism to produce sizable variations. If the HeII-HeIII zone is too shallow it will not be massive enough to collapse back on itself when distended and produce the compression required for the next pulsation. This implies that only a select range of stars will pulsate via the HeII-HeIII valve mechanism. This fact is clearly borne out by the observed location of pulsating stars on the Hertzsprung-Russell diagram. In a surprising way, the pulsation that we see provides us with a glimpse into the interior of a star.

5.13 The Detection of Multi-Mode Oscillations in δ-Scuti Stars - The International Campaign

Most δ-Scuti stars pulsate with irregular, low amplitude variations which give rise to complicated light curves. A typical period for these stars is 2 - 3 hours with changes in brightness of about 0.02 magnitude units. From one night to the next, however, the light curve of a δ-Scuti star can change significantly. An example of this is provided by the δ-Scuti star KU Cancri, in the Praesepe star cluster. Figure 5.6 depicts the light curve for this star and reveals a very irregular and variable light curve when viewed over several days. Such a light curve suggests that there are several different frequencies of oscillation present. At times these frequencies are in phase, producing a large amplitude while at other times they work against each other. This type of behaviour is called multi-mode periodicity.

It is this aspect of δ-Scuti stars that has attracted the attention of theorists and observers over the past decade. If one can precisely measure the frequencies at which the star pulsates one can begin to construct a picture of the interior of the star. This provides stringent tests on current models of stellar structure and promises to be a very fruitful area of collaboration between theorists and experimentalists.

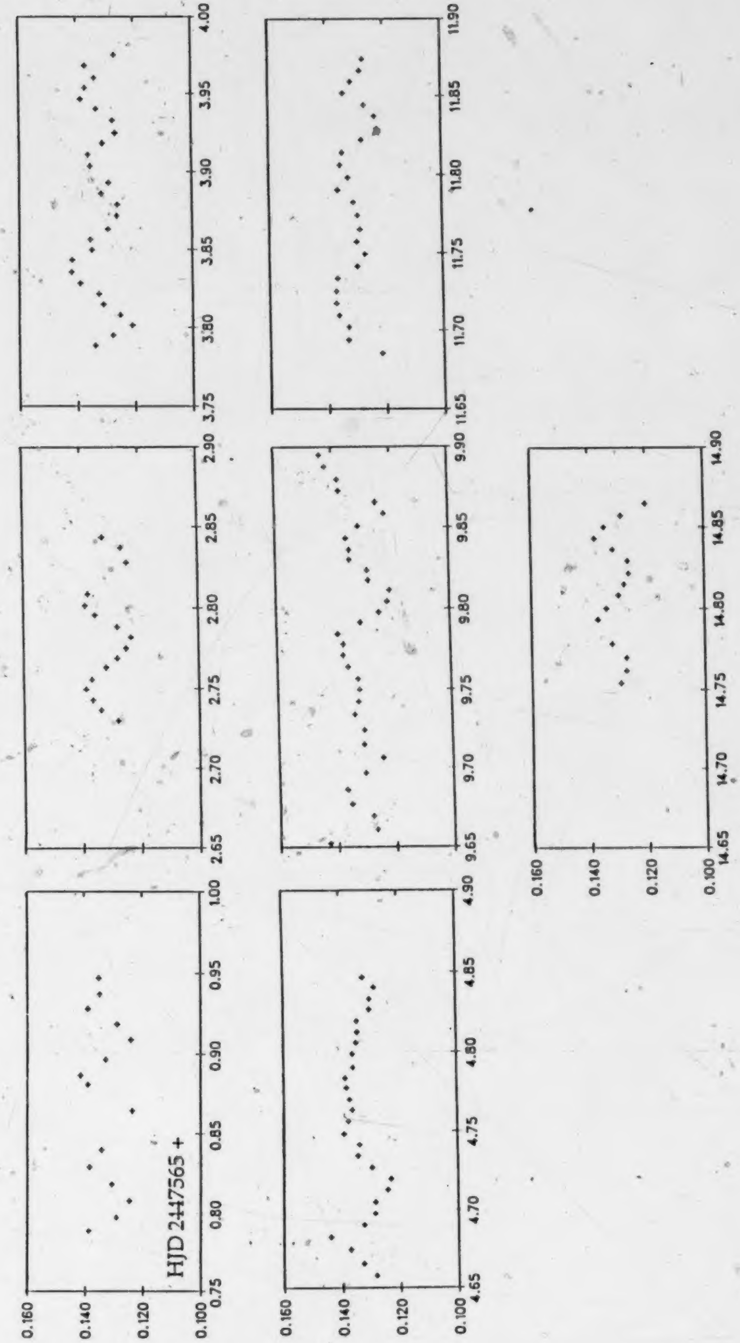

Figure 5.6 V filter light curve for the δ-Scuti star KW 207.

The program of measuring multi-mode frequencies in δ-Scuti stars is, however, fraught with a number of serious difficulties. First, the amplitudes of oscillations observed in the multi-mode δ-Scuti stars are small, often less that 0.01 magnitudes. This taxes both the ingenuity of observers and the quality of observing sites. A second, and more serious problem, however, has to do with the fact that observations at any particular observatory are interrupted each day by the daytime period in which observations of the star are impossible. This occurs with a well defined one cycle per day regularity and imposes a very strong "false" frequency on one's attempts to measure the true frequencies of variation for the star. This problem, referred to as **aliasing**, is discussed in detail in chapter 9.

One way to minimize the effects of daily aliasing is to coordinate the observations of a number of well spaced observatories. As one observatory begins to "lose" the star another observatory further west can pick it up. Providing the sky conditions are favourable it is then possible to monitor the star on a nearly continuous basis. In practice this requires that a number of observatories, on different continents, observe the same star for an extended period of time, typically 3 weeks to a month. Such coordinated observing projects are referred to as **campaigns**.

In November 1987 and February 1989 the stars HR 729 and KW 207 (BU Cancri), respectively, were the subjects of two international campaigns involving observatories located at Beijing,(Mainland China), Piszketseto,(Hungary), Sierra Nevada,(Spain) and the University of Alberta Observatory at Devon,(Canada). These stars were selected because they were suspected multi-mode oscillators. The results of the Devon observations of these stars will be reviewed in Chapter 8.

5.14 The Search for Rapidly Oscillating Peculiar A Stars - a "Failed" Project

The **peculiar A** stars (abbreviated A_p) are a subset of the A - F stars that show abnormal metal abundances in their atmospheres, intense magnetic fields and variations in the strength of spectral features. They occupy roughly the same region of the HR diagram as the δ-Scuti stars. Within this group is a small subset of stars referred to as **rapidly oscillating** A_p (roA_p) stars which exhibit rapid light variations with periods ranging from 5 - 20 minutes. The first member of this class was discovered in 1978 by Donald W.Kurtz(15) in South Africa and in the intervening decade 11 more stars have been added to the list of confirmed roA_p stars.

The oscillations present in the roA_p stars are believed to be high order non-radial pulsations. This means that the stellar surface is pulsating in a complicated, at times "checker-board" pattern. Figure 5.7 shows a set of possible modes of non-radial pulsation. The numbers designated by L and M refer to the number of nodes or stationary points on the oscillating surface. L values indicate the total number of nodes parallel to the equatorial plane of the star while the M values indicate the number of nodes perpendicular to the equatorial plane. Some parts of the surface are expanding outward and are somewhat brighter than neighboring regions that are falling inward. Such patterns have been observed directly on the surface of the sun and are most probably due to acoustic waves trapped and reflecting within a layer bounded by the photosphere and a region deeper in the interior. As in the case of the δ-Scuti stars, knowledge of these modes of oscillation provides valuable probes into the solar and other stellar interiors. The details of this will be deferred to chapter nine.

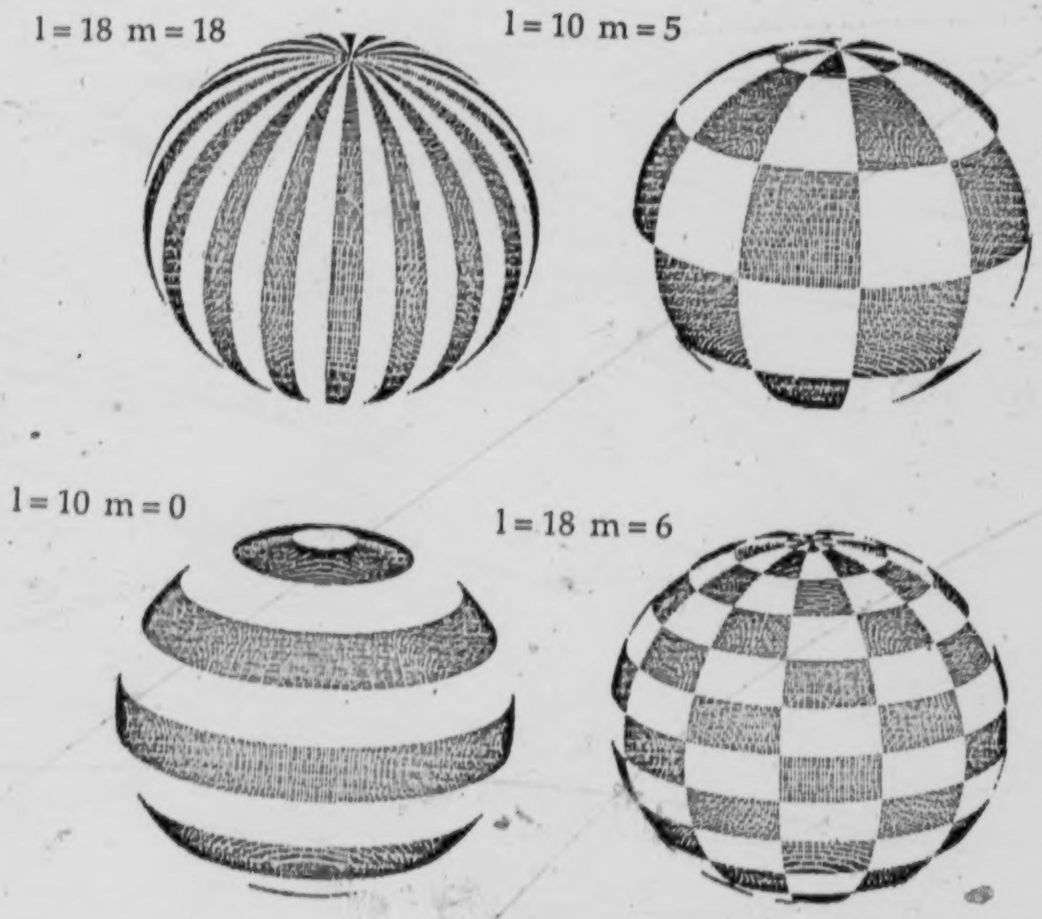
l = 18 m = 18
l = 10 m = 5
l = 10 m = 0
l = 18 m = 6

Figure 5.7 Nonradial modes of oscillation on a stellar surface for different values of l and m.

The light variations observed in roA_p stars are complex, low amplitude multi-mode oscillations. Similar problems attend the resolution of the modes of oscillation present in the roA_p stars as in the case of the δ-Scuti variables. As well, the amplitudes of the light changes are even lower, usually on the order of a few milli-magnitudes and subject to marked variations from night to night.

In the fall of 1986 an observational program was begun to monitor a group of peculiar A and F type stars for possible rapid oscillations. Fifteen stars were monitored with no conclusive evidence of variability being found. By the fall of 1987 the project was abandoned.

The decision to terminate this program was based on a number of considerations which are also revealing of the nature of experimental science. Although I was unable to detect rapid oscillation I am not at all justified in assuming that the stars I observed are **not** roA_p stars. In order to conclusively eliminate any star from the list of possible roA_p stars would require considerably more data than I have at my disposal. Even if I did convince myself and colleagues that a particular star was **not** a rapid oscillator, without any clear theoretical picture of which stars ought to be roA_p stars and which should not be, demonstrating that a particular star does not oscillate is of little or no scientific value. From the outset, my research program was designed only to accommodate the positive finding of rapid oscillation. In order for sense to be made of negative results a more ambitious survey of stars would need to be undertaken. For purposes of a doctoral project such as this, that would have proven prohibitive.

Thus, after nearly a year of negative or inconclusive results the project was abandoned for more "rewarding" projects on eclipsing binary and δ-Scuti stars. These projects fit within well established traditions and the problem of assessing the value of results is much simpler. All of this points towards the highly fallacious character of the naive inductivist models of science. Without any clear theoretical structure the ability to make sense and ascribe value to an astronomical fact is highly dubious. It is not at all clear what value lies in the suggestion that the "suspected" roA$_p$ star HD32655 is non-variable. On the other hand, stating the B magnitude amplitude of variation for 42 Persei is meaningful and, with respect to ellipsoidal variable star research, a fact with some value content. In textbook and curricular portrayals of science, careful attention should be accorded the interplay between theory and experimentation.

One method of developing the theory-experimentation interplay within school science portrayals would be to introduce, via historical episode, the paradigmatic or thematic structures of important scientific ideas. Thomas Kuhn's discussion of the discovery of oxygen(15) or Gerald Holton's analysis of Millikan's measurement of the fundamental unit of charge(16) could be used effectively and efficiently within most high school science curricula to help draw out the interplay between theory and experiment. As Kuhn puts it

> ... the sentence, "Oxygen was discovered," misleads by suggesting that discovering something is a single simple act assimilable to our usual (and also questionable) concept of seeing.(17)

Kuhn puts discovery and seeing in a "paradigm dependent" context concluding that sense can be made of experiment only through the intervention or even upheaval of a prevailing paradigm. Similarily, it is difficult to explain Millikan's "discovery" of the charge of the electron without understanding, as Holton suggests, Millikan's commitment to the thematic element of discreteness.

Along these same lines, Hodson(18) alludes to the problem of the creation of an erroneous curricular distinction between "facts" and theories. Too often the complex nature of experimental science is collapsed into a school science parody of science which fails to adequately represent the diversity of experimental science. At times, in the absence of adequate theory, experiment unfolds within an essentially inductive framework. The project on roA$_p$ stars (with necessary changes in experimental design) could serve as an example of this. At other times experiment can be deductive or demonstrative in nature and act as an articulation of an existent paradigm. The studies carried out on 42 Persei or on the δ-Scuti stars would fall within this classification. Still other experiments may be of a critical nature, designed to test a specific hypothesis. The attempt to detect the alleged M-type companion of 42 Persei alluded to earlier would exemplify an experiment of the critical kind.

5.15 The Variability of HD73819 and Serendipity in Science

The history of science is replete with examples of unexpected or serendipitous discoveries. Roentgen's discovery of X-rays, Becquerel's discovery of radioactivity or Jocelyn Bell's discovery of pulsars are but a minute fraction of the list of important findings wholly unexpected by the science of the day. Less significant but equally unexpected findings are common occurrences in science. An example of such a serendipitous finding is the variability of the star HD73819.

Listed by Johnson(19) as one of the Praesepe cluster UBV standards, HD73819 was used in the February 1988 campaign of observations of the δ-Scuti star BU Cancri. The star HD73819 was chosen as one of two comparison "candles" against which to monitor the changing brightness of a known δ-Scuti star. Very early in the campaign, however, it became clear that something was "odd" about this star and the conclusion was eventually reached that HD73819 is itself a variable star. Figure 5.8 shows a light curve depicting the difference in brightness between HD73819 and another standard star (HD 73711) on four different evenings. It is clear that the amplitude of at least one of these stars is variable and evidence will be presented in chapter eight which suggests that it is HD73819 which varies with a period of approximately 4.12 hours.

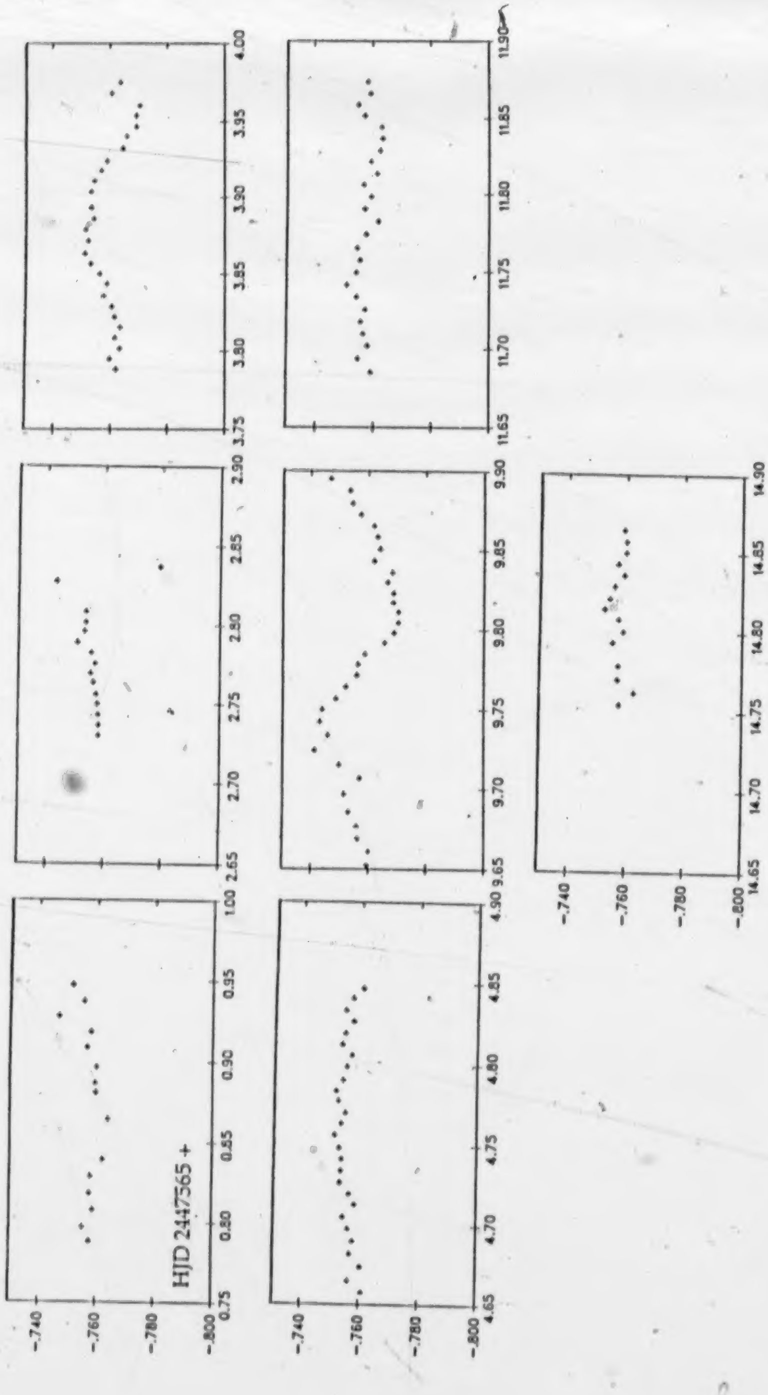

Figure 5.8 V filter light curve for the star HD 73819 on 4 separate evenings.

The variability of a faint standard star is hardly a surprising discovery; variability of comparison stars is a problem that all too often plagues this type of research. This point does, however, illustrate the simple fact that normal science (using Kuhn's notion) is very effective at uncovering anomalies and that research can at times take a very circuitous route, often arriving at a quite unexpected destination. To follow Kuhn a bit further, the discovery of the variability of HD73819 presented an anomaly that was easily absorbed within the paradigm in place at the time.

It is this unexpected nature of science that creates an air of excitement that is altogether lost in the rational reconstructions of science that often occupy the pages of science texts. In the next chapter some of the excitement surrounding the unexpected behavior of HD73819 will, I hope, be conveyed in a narrative manner. The serendipitous nature of science contains within it a highly infectious "charm". Even though rules of scientific conduct (methodological as well as ethical), equipment, facilities, the nature of the problem and even talent constrain one's research, even the most mundane science is never completely empty of the possibility of surprise. It often seems that in our zeal to be rigorous or thorough in the presentation of science to students the simple but utterly fundamental notion of serendipity is lost, shunted to the sidelines as something not really part of science or at best anecdotal.

5.16 Conclusions

The astronomical research described in the present chapter will form the context for the narratives that follow in the next chapter. More technical discussions of this research have been deferred to Part B of the thesis, chapters 8,9 and 10. While this has, I hope, made the thesis more readable, it is worth noting in conclusion a suggestion made by Ian Mitroff concerning the way in which scientists might consider presenting their research:

> For a long time I have thought of writing a paper with the following format. Each page of the paper would have a line down the middle. On the right half of each page (perhaps corresponding to what is currently attributed to the left half of the brain) would appear the standard, traditional account of the most tightly controlled inquiry I am capable of doing. On the left half (right brain) would appear a blow-by-blow, stream of consciousness account of what I thought, felt, and so on, as I went through the pain, sweat, and joys of doing the study. There would be no attempt to tie these two together, existing with and without the other. No comment would be given.(20)

Given the furious competition for space in most journals it is unlikely that Mitroff's suggestion will ever be heeded. It is, however, worth considering whether Mitroff's idea might not be used effectively in science education. Derek Hodson, for example echoes an idea similar to Mitroff's when he considers ways in which students may begin to understand the complexity of the interaction between a scientist's personal experience of science and the public expression of the science. Hodson notes that student understanding of the distinction between the private and public dimensions of science could be reinforced:

> ... through children's own writing: sometimes accounts of laboratory accounts of laboratory experiences expressed in "private language" and sometimes descriptions of procedures and results expressed in community "public language".(21)

Hodson's suggestion can be pushed beyond just illuminating the distinction between personal and public knowledge. As alluded to earlier, narrative form can be used to illuminate the many dimensions of science. Both students and teachers may well benefit by exploring their own personal engagement with science. In the following chapter a series of anecdotes will be presented which attempt to do just this to my own personal experience of astronomy.

Notes Chapter Five

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Chapter Six
Exploring One's Personal Science

6.1 Introduction

In "Polanyian" terms, all knowledge is rooted in and framed by the personal knowledge of the individual. Our thoughts are also shaped by the lore of a much larger culture of which we are members. We dwell within our ideas and are, to a very large extent, only subsidiarily aware of the presuppositional nature of these ideas. My research as an astronomer and teacher is so rooted. In this chapter the personal dimensions of my being an astronomer and teacher will be explored. My reflections, as short anecdotes, will attempt to uncover my own personal science and how I communicate this to others as well as exploring the way in which aesthetic and thematic dimensions manifest themselves in what I do. Validity will be lent to the ideas of personal science discussed in previous chapters if the present stories "resonate" with the experiences of others. The stories will also afford opportunities to reflect on the teaching of science and the benefits that can accrue from attending to one's personal science.

6.2 Pedagogic Links

It is my contention that there is a strong pedagogic current at work in one's research as a scientist. In coming to see **my question**, in probing and testing ideas, in anticipating and planning how I will engage my whole self in my research I live out many of the traits and behaviors that I would have my students experience and display. My choice of becoming an astronomer and a teacher is a conscious act of personal affiliation, of apprenticeship to a community which, according to Polanyi, cultivates the lore and traditions that form the presuppositional matrix of my discipline. My mastery of this cultural lore carries with it an acceptance of the authority and a commitment to the standards set by the community. As well, I become a participant in the transmission of this lore to others.

It is in this sense that I contend that there is a pedagogic link to my research. Also, it should be made clear that I am not suggesting a view of pedagogy that rests in an emulation of what I do as a scientist. To do this would be to give up, from the outset, any sense of this pedagogy. What a scientist does is an outward manifestation of what animates him or her. It is this animating (personal) center that I wish to uncover. To do this I will consider what I do as an astronomer from a phenomenological (or human science) viewpoint.

This may seem like a marriage of unlikely partners and yet it is not without precedent. The writings of Loren Eiseley(1) provide an exemplar of what follows. Van Manen(2) and Suransky-Polakow(3) have provided examples of how the phenomenological approach can be used to explore one's own lived experience and to share this with others. According to Van Manen, as well as being a reflection on one's own experience:

> The point of phenomenological research is to "borrow" other people's experiences and their reflections on their experiences in order to better be able to come to an understanding of the deeper meaning or significance of an aspect of human experience.(4)

In what follows a series of short anecdotes will be given. While the anecdotes are not written with the degree of rigor one would expect of the writing described by Van Manen, they will create a reflective situation from which to develop a pedagogic link to science teaching. Some anecdotes will provide insight into the nature of "doing astronomy" at a small observatory. Some anecdotes will point more directly at what it is like to convey "my astronomy" to other persons. In their entirety the anecdotes are an attempt to explore the question "What is it like to be an astronomer?" and to convey to the reader a sense of my personal engagement with science and science teaching.

6.3 What's a Falling Star?

> *"Dad, what's a falling star?"*
>
> *The meteor had stopped us both in our ascent of the long stairs to the observatory. My eleven year old son Nathaniel likes to accompany me when I go to the observatory-most likely because then he can stay up late, to those mysterious hours past midnight.*
>
> *Without thinking I began my reply.*
>
> *"Well, the Earth is always being hit by bits of stuff. Usually tiny rocks, almost just specks of sand are what you see when you see a meteor. They are going so fast that they heat up from the air hitting them and burn up. Poof, a bright flash and then they are gone." "You mean they aren't falling stars?"*
>
> *"No, just tiny bits of rock."*

My answer was technically correct but was it the "right" answer? So easily I slipped into the role of science teacher but, in this instant was I a good teacher? Consider the question again-what's a falling star? My answer curtailed the possibility of this question growing, of becoming more than I assumed it was. Notice as well, that without thinking I did not acknowledge the term 'falling star'. This is a wonderful, child-like and rich term. It was rooted in Nathaniel's perception-he saw a star-filled sky and then, without warning one fell. His question was a genuine question with an openness that invited our mutual exploration of falling stars. Instead, I offered a speck of sand in place of his star. Perhaps a better teacher would have replied...

"A falling star. Do you think it's a star? If stars fell, wouldn't the sky be empty after a while?"...

The anecdote challenges me to work constructively with the student's preconception of an idea. Although I have no doubt that eventually it is desirable for the child to acquire a conception that could be considered "scientific", I cannot simply brush the prior conception aside. I also must consider, pedagogically, at what point will conceptual change meaningfully enhance that child's understanding of science. Eventually I would want the child to understand the physical nature of the meteor - a mere speck of cosmic dust - and to marvel at how such a speck could produce such a brilliant and surprising sight.

The anecdote also helps bring home the critical role of question in science teaching. It challenges us to consider whose question it is that we wish to honor, the teacher's or the student's? In attempting to arrive at a pedagogy of science teaching that acknowledges the personal dimension of science what role will questions play?

Consider the role of question in my research as an astronomer. First my questions are just that, they are **my** questions. They spring from within me and have been formed by my experience of the world. Further, it is these questions that motivate the research. Much more than answers, I search for meaningful questions. In our attempts to represent science before our students do we do justice to the nature of question?

6.4 Trust

> *The car is warm and I'm on my way home, ready for sleep. Did I shut the drive off?*
>
> *Nagging doubts start to creep in. I remember closing and locking the shutter, putting the telescope in its resting position but did I remember to shut off the motor drive?*
>
> *I glance at the dashboard clock -- four a.m. An image keeps playing across my mind. I see myself going through the usual closing-down procedures: rotating the dome to its resting position, closing the shutter, putting in the dark-slides. The dark-slides! Did I even close the dark slide on channel B? Bother!*

> *All is quiet except for the occasional crunch of the snow beneath my feet as I stand, shuffling in the dark, peering across the threshold into the dome. Everything is as it should be. The telescope is resting comfortably, dark-slides in place and drive off. I glance at my watch, four-fifteen. Well, at least I'm sure.*
>
> *As I near the turn-off for home I begin to wonder, did I remember to lock the dome?*

Simply put, science operates on trust. From my first, tentative solo "flight" at the dome to the present, I have been entrusted with the care of a valuable and, in the hands of an incompetent operator, potentially fragile piece of equipment. Michael Polanyi made an amusing observation about the supposed repeatability of scientific observations.

> "Supposing you [the student] could somehow get the use of an observatory or a chemical laboratory, you would probably damage their instruments beyond repair before you ever made an observation.(5)"

But this is only a minor aspect of a deeper trust that must exist between a graduate student and supervisor or between colleagues before science can be done. For me this sense of being trusted (and hence being able to trust) came early in my association with my supervisor (Hube). This deeper trust is an affirmation of my sense of judgment and competence as a colleague.

Polanyi finished his comments quoted above with the additional observation that, even if the student was able to make an observation of some quoted "fact" in his science text and if this observation contradicted the established result, the student would rightly conclude that he was mistaken. The road from naive observation to scientific fact is long and convoluted and has been carefully mapped out by Jerome Ravetz(6). Without a sense of trust, the scientific community would be paralyzed. In areas outside his or her own expertise, the scientist relies upon the factuality of the published results in much the same way that the student trusts in the integrity of the lesson. Even within one's specialty there is a trust that observations have been obtained and results arrived at in accord with standards set by a particular scientific community. The individual corroboration of every reported detail used by the scientist is, in a practical sense, impossible.

In science there is a continuous, creative tension between allegiance to authority and dissent from this authority. My apprenticeship in astronomy gives me the sense of value necessary for the application of the standards set by the astronomical community. I form a willing affiliation with this community. The trust accorded to me as a member of this community also empowers me to dwell within my science in a personally responsible manner. Thus, I am able to dissent, in a personally responsible way, from the dogma of the community if the need should arise. Polanyi asserts that:

> while science imposes an immense range of authoritative pronouncements, it not merely tolerates dissent in some particulars, but grants its highest encouragement to creative dissent.(7)

For the teacher and the student, trust in the classroom has a similarly real and palpable quality. Bollnow(8) has described "trust" as one of the three essential virtues of an educator (love and patience being the other two). It is by creating a bond of trust between the student and the teacher that the student is willing to pour him or herself into the ideas being taught. Trust is a necessary condition for indwelling and is the leavening agent of true education (ie. as distinguished from mere training). The teacher, by holding a conviction of trust in the student (as opposed to just "stating" it) creates the atmosphere in which the student may become trusting.

Only within such an atmosphere of trust will indwelling occur. The portrayal of science as a fragmented collection of verifiable facts, cut off from its communal and mythic roots, places no formal value in this. A masterful teacher will still create the requisite conditions allowing his or her students to dwell in the ideas of science but this will be seen as incidental to the nature of the ideas themselves. A science education centered on the notion of personal science, however, would value indwelling as an essential curricular aim and an integral part of science. Indwelling is part of one's participation in knowledge and not just a "pedagogic tool". In such a science education the student will be empowered to both trust in and, when the need arises, dissent from the ideas being taught.

6.5 All in a Night's Work

> *The sky had cleared unexpectedly. My walk to the bus stop was an impatient one . The ride home seemed interminable. The sky had been overcast most of the day and I was looking forward to a quiet evening at home and then this!*
>
> *Supper was rushed. My notes, star charts and computer disks were hurriedly assembled. A large thermos of coffee and various goodies were stashed away in my knapsack (just in case the seeing held till morning). The kids didn't seem to be too disappointed that I was going but my wife's eyes told much more than her stoic smile. This was the fourth night in a row and the weatherman had promised that last night was the end of the clear skies.*
>
> *"See you in the morning".*
>
> *The air was crisp and cut at my nostrils as I stepped outside. The rapid clearing had driven the temperature downward. The car complained a bit and then spluttered into action.*
>
> *"Its 5:59 and the weatherman is calling for clearing tonight with overnight lows of -21 in the city, -26 in outlying regions. Sunny tomorrow with increasing cloud in the afternoon. Now the news..."*
>
> *I feel tired as I back the car up the driveway. Its only a 40 km drive to the observatory but this always seems to be the worst part of the night. I'm out of the city quickly and as I reach the crest of the overpass I get my first unobstructed view of the*

western sky. A pale gray-pink glow all along the horizon with an inky, velvety black above tells it all. I've got at least six hours of clear sky and almost certainly another complete night. My tiredness begins to give way to a feeling of anticipation, of excitement.

As I near the observatory the thought crosses my mind that Jim Unger (creator of the cartoon character, Herman) must know an astronomer. His cartoons so accurately reveal my own quirks. I drive with one eye (luckily my good one) on the road while I crane my neck into unlikely positions to get a glimpse of the sky. This is an endless source of consternation for my wife when we drive anywhere in the country on clear nights. Every once in a while the astronomical community is saddened by the loss of one of its own in a car crash. I wonder, is this ....

I reach the observatory intact. It's isolated out here, on the edge of a university botanic garden and I get an uneasy feeling as I step out of the car, alone in the dark, and fumbling with the heavy lock on the driveway gate. A small sense of relief comes when I jump back in the car and proceed further into the woods towards the observatory compound. I lock the compound gate behind me. In the middle of the now dark and very still woods I feel oddly secure and proceed quickly to get the telescope "up for the night". The computer and electronics are switched on and the telescope drive, reluctantly, begins it's night long task of tracking the stars. Its cold, my fingers are numb after only a few minutes of work in the dome. The shutter on the dome slowly grinds upward revealing a beautiful, clear and steady sky. Tentatively at first, the dome rotates to present the region of the sky that I will follow tonight. My star is in the constellation Auriga. No, not majestic Capella that presides over the winter sky. Tonight I will look at one of the least of her brethren, HD 32655, a star not even visible to the unaided eye.

It often seems a disappointment to others when I tell them I'm studying "HD 32655". Perhaps they expect extravagant names like Betelgeuse, Al-

debaran or Zuben Elgenubi. Yet there is something that is remarkable in the name HD 32655. The HD stands for Henry Draper, a wealthy amateur astronomer who funded, at the turn of the century, the most extensive catalogue of stars in use. Almost half a million stars are now contained in this and other catalogues with information on position, visual brightness, type and so forth. This is no mere cataloguing. It speaks to me of a deep sense of reverence and dedication with which past astronomers have approached their craft. A legacy from which I draw.

My duties in the dome are for the moment ended. I have located HD 32655 as well as it's comparison star and begin the night long vigil of measuring the brightness of the stars. I move to a small annex adjoining the dome; the warm room. Sitting amid the computer and electronics I watch the counts slowly fill up the computer screen. Every ten seconds a number scrolls onto the screen. No, nothing as romantic as Galileo or Herschel at the eyepiece. I look at numbers, not the stars. The only time I "see" HD 32655 is when I carefully center it in the field of the photometer. This is an imposing looking instrument, not unlike an elaborate light meter, with which I can measure flickering in the stars far more subtle than the twinkling we see with our eyes. This is perhaps the greatest "let down" to those who innocently ask if they could someday look through "my" telescope. For some, that's also the last question they ask. Their image of me, sitting in a tiny room looking at numbers is so far removed from their notion of what astronomers do, that they shake their heads in disgust and soon change the subject.

But for those who are persistent and open to my telling, a different tale can unfold. Sitting, watching the counts come in is, in a highly abstracted way, my listening to a star more than 100 light years away. What story can such a star tell?

There is always a sense of anticipation as I wait for the numbers to come. Maybe tonight HD 32655 will give a clear indication of variability. Nothing *coldly objective here, I'd be overjoyed if, after so many nights of observing, something clear and unambiguous showed up. I'm searching, looking for new members of a very small group of rapidly pulsating (twinkling) stars discovered over the past decade. To date there are only a dozen or so known and most of these are visible only in the southern hemisphere. It is easy to see why there are so few known. These stars vary in brightness by typically less than one percent and rapidly, on the order of five minutes to half an hour. Think of it, a star, beating, pulsing like a giant heart.*

I put my gloves and toque back on. Time to begin my own periodic behavior; back and forth through the night I must check the position of the dome, make sure the star is still centered in the photometer and keep an eye on the sky conditions.

Everything is fine, a perfect night. The sky is clear and deep and the telescope is tracking true. I pause as I leave the dome and gaze upward. The Milky Way, dotted with star clusters hangs overhead. What other science can provide such moments? The cold jars me from my reverie and I head for the warm room.

The night wears on. The seeing has held, it has been one of the best nights of the year and the data that I have collected are very good. The weariness has not hit yet, that comes later when I reach home. Right now I concentrate on closing up. A few final observations and then the telescope is "put to bed". The dome is closed, the electronics and computer switched off. Its almost six, dark and very cold. The same feeling of vulnerability and aloneness comes as I leave the compound and make my way to the car. Always the same sense of relief when I'm finally on the road, travelling home. I'm wide awake thanks to the chill of the cold morning air and very satisfied with a productive night.

My doing of astronomy grows out of a context. The context is made up of my family and the sacrifices which this profession sometimes imposes on them. During the observing season which stretches from late August through April many nights are "handed over to the stars." Plans are canceled or changed at the whim of the sky. Wedding and birthday parties have been left early or all together missed.

My research is done at a small observatory as opposed to a "Palomar-like" setting. Often I work alone and, in the winter months when the nights are very long and cold, this is always a source of some concern(9).

As well, the astronomy fits within an established research tradition. In my case it is the analysis of the light from variable stars. All of this forms part of the matrix in which my research unfolds.

This is all very mundane and yet friends and students often ask "what's it like to be an astronomer?" or "what do you do at the observatory?". Both of these questions focus on the personal, human aspect of my being an astronomer and are genuine, unsolicited questions. They are more concerned with the human, lived experience of the science than the details of stellar pulsation or dual channel photometry. Yet, very little of this part of science finds its way into textbook presentations offered to students.

6.6 Force of Habit

> *Dusk is giving way to night and I am drawn, almost magnetically to the window. What's the sky like? Clear, any high cirrus? For most of my adult life I have held a strong affinity for the sky. I am an astronomer, one of those at times sleep-deprived souls who peer, or so the popular belief goes, into space with long, tube like eyes. In fact, the modern astronomer is much removed from this notion, but for the moment I feel what almost every astronomer of past centuries must have felt, a sense of anticipation for the approaching night.*

> *But am I like the astronomer of past centuries? I am looking up into a clear sky and straining to see a small patch in the constellation Auriga. Beyond the edge of visibility lies the star HD 32655. But what is this feeble light? Is it a pinhole in the crystalline celestial sphere? Or is it an inferno or perhaps a ball of gas slowly collapsing under its own weight and glowing with some of the heat being produced? Perhaps it's a ball of gas, mostly hydrogen and helium with a sprinkling of other elements, powered by a nuclear fire burning deep within its interior. And perhaps it's laced by an intricate magnetic field many times more powerful than the one that tugs at compass needles here on Earth. Maybe this star is rotating and just maybe it is pulsating, beating like some cosmic heart. This last "maybe" is the one that forms the kernel of my investigating this evening.*

Am I like an astronomer of past centuries? Am I like any other astronomer of the present? Perhaps most important, in what ways, if at all, am I like my student? These questions push to the fore the role that presupposition plays in science and in science education. My seeing(10) of a star is mediated by my presupposition of what a star is. In this respect I am very much unlike an astronomer of only a century ago. Similarly, my seeing a student is shaped by my conception of what a student is.

Both my student and I bring, unavoidably, our presuppositions with us. Unlike the student, however, I am not burdened by having to adopt another set of presuppositions. My research unfolds, is shaped by and in turn shapes my presuppositional infrastructure. For the child something different may be occurring. In addition to what he or she holds in a presuppositional sense there is also an external factor, the curriculum and the agenda of the teacher.

The force of habit is hard to break. Dewey recognized this over half a century ago when he wrote

> The history of educational theory is marked by opposition between the idea that education is development from within and that it is formation from without; that it is based upon natural endowments and that education is a process of overcoming natural inclination and substituting in its place habits acquired under external pressure.(11)

Dewey speaks of the tension between cultivating the ideas of our students in constructivist sense and imposing our adult formed conceptions via transmission. Unless our view of knowledge and pedagogy opens us to concerns such as these, the role of presupposition and the whole notion of the personal dimension of science will remain elusive.

6.7 I Bring Myself to the Data

The green phosphor dot inched its way across the computer screen--now up, now suddenly back down. My anticipation began to sour as I watched the dot's drunken antics. In its wake lay an erratic jumble of dots strewn carelessly about the screen. It was a light curve to be sure, but nothing at all like that which the previous night's data had produced.

The January clear spell had brought the unexpected surprise of warm temperatures hovering around -10 C and I was the grateful recipient of five nights of data. That week had been busy, classes were in session so I stole time from my students as well as my family. A few hours of sleep, off to school and back home as soon as classes were over. A few more hours of sleep, a quick supper with Evelyn and the children and then out to the dome. By the end of the fifth night, when the sky had finally "failed" I was weary and relieved. Now I was eager to get at the data, nearly 20 hours of it.

My reduction of the first three nights had made me hopeful. The light curves, though noisy, seemed

> *to suggest a short period variability, perhaps on the order of 10 minutes or so. And now this mess!*
>
> *With a sharp stacatto movement I hit the reset button. The computer beeped loudly as if in protest to this misplaced anger and then complied with my demands. I checked the data, redid the reduction. No, the computer was not the "culprit" - I was! Computer, empty of any human trace of wishing-for or expecting, merely replayed the same depressing jumble.*
>
> *Einstein once said that God is subtle but not malicious. Einstein was not an astronomer!*

HD 32655 has puzzled me for the past six months. Is there a short period variation present in this data? I don't know? Some days I'm convinced there is, on other days it's less clear. The road from hunch or hopeful guess to that of published "fact" is a long and convoluted one.

In its initial stage, data gathering is performed within a context of anticipation and doubt. That doesn't mean that I will alter my data to become the "fact" that I wish it to be. But clearly, from the outset, I bring myself to the data.

Nor does it mean that all data is equally resistant to my investigating. Some data readily reveals properties that will eventually become enshrined as "fact". The graphs shown in Figure 6.1 illustrate this point. Each graph is a light curve or visual record of the brightness of the star (vertical axis) related to time. In the first case (HD 32655) the curve is a jumble. The second (HD 85040) is more compelling. Also, HD 85040 is a previously published star with variability just as I have found in my own observations of it. In this case, the transition from "my" data to "fact" is an easy one. HD 32655 presents a far more problematic case.

There are no published light curves for this star. Also, the amplitude of variation in the light curve is much smaller than in the case of HD 85040. At this point I must bring my knowledge of photometry and error analysis to bear on the data. Also, knowledge of the peculiarities of my equipment and observing site become part of the **judgment** that I must impose. I know that at any instant in time the Earth's atmosphere can vary enough to produce changes on the light curve much as I see them now. Is this just "noise" that I'm looking at? Perhaps, but there are mathematical techniques that I can apply that allow me to "peer through" the noise. One of the most powerful of these is the **Fourier transform**. This is an algorithm that I can apply to any light curve, periodic or random. If there is any periodic variation present in the light curve it will appear as a "blip" or vertical line in a transform graph. The position of the line is directly related to the frequency of variation. The graph of a Fourier transform is called a frequency spectrum. Random variations in the data appear as "grass" or "hair" throughout the entire frequency spectrum in the transform. A Fourier transform for HD 32655 is shown in Figure 6.2.

The Fourier transform for HD 32655 (11-10-86) does show some indication that there is a periodic component to the light curve. It is consistent with a star that is brightening and dimming with three (at least) different periods: 14.22 minutes, 12.20 minutes and 10.66 minutes. But, is this variability real?

At what point do I commit myself to the position that effect X is a real phenomenon? At what point in the research does X become a fact? These are among the most difficult questions that I, the researcher, face. Ambiguity, at least at some stage of the research is unavoidable. How different it often seems in science classes. Terms like "closure" and "clarification" seem to be preeminent. Ambiguity seems to be shunned at all cost. But is a little ambiguity such a bad thing? I can only feel the sense of ambiguity in this data because I bring to this data my own expectations and hunches.

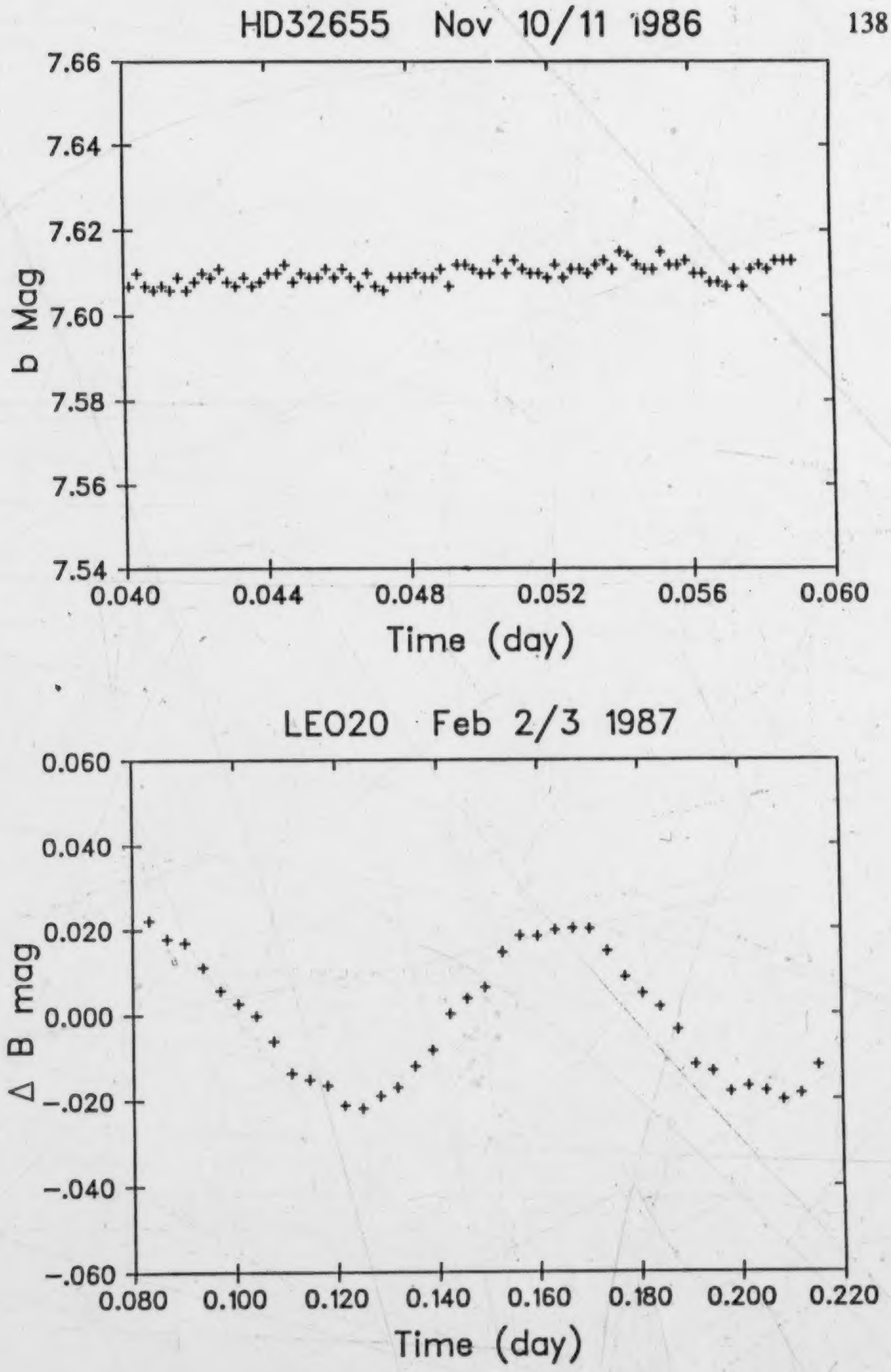

Figure 6.1 Light curves for the stars HD 32655 and HD 85040 (= 20 Leonis). HD 85040 is a known δ-Scuti variable. There is little ambiguity in accepting that the light curve provides evidence of variability. The light curve for HD 32655 is far less "clear cut".

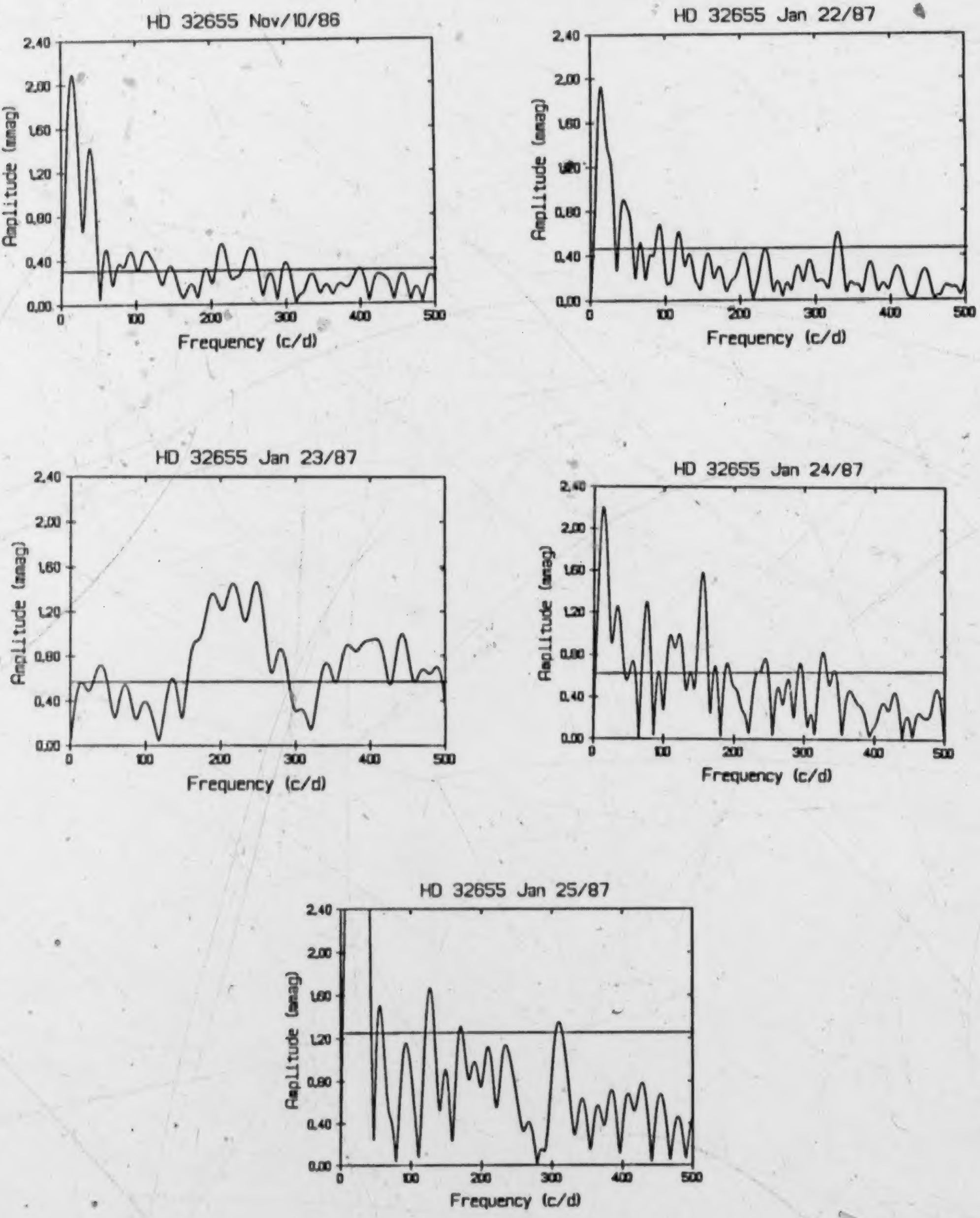

Figure 6.2 Fourier transforms for HD 32655 for the nights: Nov 10/86, Jan 22/87, Jan23/87, Jan24/87 and Jan 25/87. There are no stable features appearing in all transforms.

If, at some future time, I settle the question of whether or not HD32655 is a rapid oscillator then I can add this datum to the store of public science about A type stars. But it is also at this point that I will begin to lose my particular interest in HD32655. The doing and experiencing of science rests precisely within the grappling with ambiguities, the following of hunches, with the successes and failures of one's ideas.

6.8 Midnight Conversations with Tom

> *"I found it!" Tom's enthusiastic announcement preceded his entrance into the warm room by several hurried steps. Nova Andromeda had finally yielded to his searching. It was - 20 C and I was comfortable in my chair watching the counts come in on HD 32655 but, not wishing to dampen Tom's enthusiasm, I followed him back to the portable telescope that he brings along on the nights he accompanies me to the dome. Tom is an ardent amateur astronomer and had introduced himself to me several months ago. At first I thought it would be great to have an "assistant" along. The nights can be very long, especially in the winter and there are times when an extra pair of hands are useful. Tom, however would have none of that-he had his own observing to do. Oh well, the company was welcome and at times we do have stimulating discussions.*
>
> *The snow crunched loudly under our feet as we approached the telescope. In the telescope a small asterism presented itself in the middle of which was a faint, perhaps reddish star.*
>
> *"See it? To the bottom right, about ninth magnitude."*
>
> *We both compare the clumping of stars in the eyepiece with what appeared on the star charts. After a few minutes I agreed, indeed this was likely Nova Andromeda.*
>
> *"Too bad you don't have a photometer on this" I offered mischievously, knowing the conversation that would ensue.*

"Why do you always have to measure? Isn't it enough just to find it, to see it?" Tom's questions had a note of exasperation attached to them.

"But isn't it more satisfying to actually measure, to be able to say something more than 'I found it'. Isn't this where the astronomy really begins?"...

An evening several weeks later and I'm delighted by the performance of the equipment and the quality of the data coming up on the computer console. Tom has come into the warm room to warm up with a cup of coffee. He watches as I make a few notes in my observing log and make a quick estimate of the noise in the data.

"I don't know how you can do this night after night", begins Tom. "Just sitting there watching numbers. It seems so boring, so tedious."

"It's nights like this that make it worthwhile. Look at this," I slide my observing log over to Tom. "Look at the noise level, less than 3 millimagnitudes, that's excellent. With this data I may be able to say something definite about HD 32655. I don't know, I think this is kinda fun."

"Look at it this way," I continue, "I'm looking at a star that probably no one else in the world even cares about (yet). There's an adventure here, and a challenge. This star might be a rapid oscillator. Only good quality data like this will help tell me. If it is, well, I can publish my results. But even more important, if I can get a good fix on nonradial modes, that can give a lot of useful information on a star."

"And if it isn't, then what?" counters Tom.

"There are a lot of stars up there, a negative result is still a useful one."

"But where's the astronomy in this", continues Tom unconvinced. "You might as well just use a computer to gather your data and pick it up in the morning. I don't know, this just seems like a job, no "romance" to it."

"I wouldn't go that far. It might be nice to have the observatory completely computerized but I would miss physically being here. I still love looking into

> *the sky, setting up on the star. There is a "romance" to what I'm doing, but it is different."*
>
> *"I guess we are just astronomers interested in different things."*
>
> *"I guess so."*

The astronomer in me pushes in the direction that I challenged Tom with; the teacher in me tugs in the other direction. There is a tension here between the demands of the discipline and the demands of teaching. The term amateur has acquired an uncomplimentary connotation that obscures the root from which the word derives. The amateur is motivated by a deep affection (love) for the science. In our age of technique, however, the love of the amateur is diminished against the demands of technical expertise. The **training** of scientists rests heavily on the acquisition of correct technique.

Despite my necessary acquisition of technique, I too act out of a deep sense of commitment to or love for my discipline. In this both the professional and amateur may share a common experience although, as Tom and I agreed we are both "astronomers interested in different things."

This now introduces the tantalizing question-as a science teacher whom do I most want my student to be like? What pedagogic values are present in the amateur's view of science that may be obscured in the professional's view (and vice versa)? This is not a simple question and yet, historically it would seem that science curricula have tended to emulate the expert. Paul Feyerabend maintains that science is too much in the control of experts (the scientists) and that for science to avoid stifling dogmatism there must be a place for both the expert and the amateur(12).

6.9 There are no Green Stars

"Over there, just below that brilliant blue star ..."

My guest turned to me with a quizzical expression just discernible through the dim light that enveloped us.

"Blue?"

His voice confirmed his question and brought me back to the fact that there was more to seeing than meets the eye.

"Sure it's blue, look above it is a brilliant red star, Aldebaran, the blood red eye of Taurus the bull."

My guest, a man several years my senior peered upward, craning slightly as if to get a closer look.

"You know, I can see a bit of red and, ... Yes that one definitely is bluish. Well, you know I always thought they were just white."

"That probably makes sense, the rods in our eyes are not as sensitive to color as are the cones. In low light conditions we naturally favour the use of ..."

My guest was peering about, I broke off my homily on the eye. That could wait. My guest was understanding something much more significant at the moment.

"Over there, that bright one, it's kind of yellowish white", he pointed to Capella. I agreed and we spent several minutes re-looking at stars my friend had observed many times before but never really seen.

"Are there any green stars?"

"No", I replied, "there are no green stars".

We so naturally assume that others see what we see. This is especially true of those things that we "know best". Most likely I have forgotten at what point in time I actually began to see colors in stars. This goes back to the idea that seeing is mediated by theory. Popper(13) addresses this at length and makes the point that we do not **have** observations, rather, we **make** observations. Our making of observations is always preceded by interest in a question or a problem. Simply looking-at something may be passive but observing something must be active.

Perhaps I began to see the color in the stars when I understood that color should be visible. A direct application of this to science teaching is found in Willson(14) and

Norris(15), who make the point that, for many experiments in science, observation is meant in a highly abstracted form. The eminent physicist David Bohm writes:

> At one time scientific instruments, such as the telescope and microscope, could have been considered as direct extensions of the senses, but today, the connection between experimental apparatus and human experience is becoming increasingly remote. The realm of physics is now that of perception through the mind, and theory dominates over experiment in the development of the scientific perception of nature.(16)

The term "observation" often becomes a highly theory-laden metaphor. When this happens it is impossible to separate inference from "simple" observing. Our portrayal of observation in science education is often very deceptive.

6.10 Satisfaction

> *My eyes refused to focus as I looked into the eyepiece. It took effort but after a few seconds I began to see the star and proceeded to gently center it in the photometer. Slowly, deliberately, I pulled the eyepiece out of the light path of the photometer and reached back for the start button on the computer console.*
>
> *The normally loud beep was muffled by my parka hood as the computer began the first of three, 40 second long measurements.*
>
> *The back of my legs brushed against the chair and partly of choice but mostly out of submission I dropped down. Despite the bone chilling cold I felt flushed, my face pulsing gently.*
>
> *A number appeared on the computer screen. The computer, with seeming indifference to my attempt to doze, mocked me with its "stamina" as it announced that it had completed the integration and was beginning yet another one. I looked at the number, the counts appeared normal.*
>
> *Looking up, along the dark shadow of the telescope and out the open slit of the dome I could see the Praesepe cluster hanging in a dark and very*

steady sky. But the stars and the cold made little impression on me, my thoughts were fixed on the impending beep from the console. In forty seconds I would have to stand and move the telescope to the next star.

This curious dance of man and telescope, moving at two minute intervals between three stars in Praesepe, had begun over four hours ago. There was little point in going into the warm room, no one would "cut-in" in this dance and the celestial band showed little evidence of wanting to stop either.

Another beep, the same as the previous one, and yet somehow insistent, urged me out of my seat. With fumbling motions I pushed the buttons on the hand held control and eased the telescope to the next star. The dance continued.

Rather than sitting down I made my way to the doorway of the dome. A gentle brush of icy air greeted me as I opened the door and stepped outside. The motion felt good but my legs were leaden and my lower back was aching. Leaning against the dome, my eyes played across the northern sky. Ice fog was settling low in the sky and a soft auroral glow began to rival the fainter stars. I pushed myself away from the dome and rejoined the telescope.

Groping about on the floor beside the console, my hand found the thermos and with effort I hoisted it on to my lap. In the faint greenish glow from the computer screen I guided the steaming contents, the last of my tea, into the frozen cup. A cloud of steam swirled upward coating my glasses with a gentle fog. The warmth of the cup reminded my fingers of the warmth of home. I gingerly put the cup to my lips and sipped in the warmth.

The dance was slowing now, Praesepe had sunk low in the west and the counts were becoming noisy, too noisy to continue. For over six hours we had swayed, telescope and I, back and forth through this bitter February night. It was a good dance, I felt a sense of satisfaction as I closed up the dome and made my way home. The pushing, the turning just one more hour into two and then into three, the

> *challenge of going until the sky would offer no more, until I could offer no more, were part of my satisfaction.*

The contextlessness of textbook portrayals of science leaves an immense gap in the public perception of what it is actually like to do science. How many students realize even a small part of the physical discomfort that an archaeologist might face during a dig in the arid regions of Mexico or the mosquito-plagued muskeg of northern Canada. Biologists, anthropologists, oceanographers and many others could relay stories of their own experiencing of their respective sciences.

Long before science reaches the sanitized state of the research paper or textbook it has been the product of human striving, sometimes under extreme conditions. What can account for such striving? What is it that compels an apparently sane person to endure freezing cold and a host of other physical hardships in the name of science? The answer, I believe, lies in the idea of **satisfaction**.

Part of the satisfaction comes from setting and achieving a goal. In my case the goal was to "tease out" as much as I could from an excellent, photometric night. But the reason for this goal makes sense only when seen within a broader context. That context is one based on a belief that the data I was amassing would lead to a more satisfying view of a particular group of stars. In that respect it was the appeal of the intellectual satisfaction of understanding within a broader framework that animated me and even permitted my ignoring the more immediate and physical satisfactions of comfort or sleep. Polanyi ranks this kind of satisfaction as one of the intellectual passions that motivate science and writes that:

> [the] distinctive quality of intellectual passions is largely due to the fact that they are attached to an articulate framework. A scientist seeks to discover a satisfying theory, and when he has found it, he can enjoy its excellence permanently. The intellectual passion which animates the student to grapple with the difficulties of mathematical physics is gratified when he feels at last that he understands it, but it is the

> resulting sense of mastery that gives him permanent intellectual satisfaction.(16)

In trying to explain to students why I am willing to freeze at night for the sake of some obscure and relatively unimportant star I face a challenging question. Many students see science in very pragmatic terms: science is valuable only in so far as it is useful. Those with a strong sense of moral commitment to the poor may even claim that "my" type of science contributes nothing to alleviating social problems and is superfluous, if not in fact contributing to these problems. After all, I am using some resources that could be better spent. The call for relevance in science is a valid one but it cannot be the only voice which students hear. Science must also be seen in a cultural context. For many people, including myself, science fulfills the deep seated drive of intellectual satisfaction. Science has an essential part of humanity bound up in it. While the student may not feel my sense of satisfaction, by sharing the context in which the science is done, I hope to convey an intrinsic value that science shares with art, music or literature. These are activities which also contribute little to alleviating poverty but without which we would be immeasurably impoverished.

6.11 Doubt

> *The data was too good. I noticed something odd the very first night I began the campaign on the Praesepe stars.*
>
> *Several months earlier, Michel Breger had phoned from Vienna and invited me to join the international campaign to secure continuous observations on the star HD73756, a suspected multi-period δ Scuti star in the Praesepe cluster. Observatories in Beijing, Hungary and Spain were participating*

and he was hoping I would be the North American link. I was thrilled, Breger is one of **the** *experts on δ Scuti stars.*

On that first, cold February night the sky was unusually steady, typical noise was 2 millimagnitudes or better. The program star (HD73756 or V) and the first of two comparison stars, HD73711 or C1, behaved as I expected they would. But HD73819 (or C2) was an enigma from the start. On several occasions I interupted the integrations to check the centering of C2 in the photometer. Everything was fine.

When I returned home that evening I didn't go straight to bed. Although it was nearly four a.m., I poured myself a brandy, put on some music and reduced the data by hand. By five the pattern was unmistakable. Both C1 and C2 had been picked as comparisons because they are **standard stars**. *They have been monitored carefully by other astronomers, including Breger, and are known to be constant in brightness. For this reason they serve as standard candles against which to measure the brightness of other stars. Yet the difference in brightness between the stars was not constant, it rose and fell smoothly over the four hours of data I had collected. Clearly, the differences suggested that at least one of the stars was, itself a variable. Something must be wrong, I must have done something wrong.*

The next two nights, however, strengthened the case that something was unusual in the data. On the night of February 16, 1989 the signal, which I was now confident was due solely to C2, was very strong. The data suggested that C2 was a variable star with a period of about 4 hours and a variable amplitude. I was worried, there must be something wrong with the system and yet the other two stars behaved "normally". The more secure the data seemed concerning C2, the more uncertain I became.

I wasn't ready to mention this to Doug but he "beat me to it". On the night of February 18, 1989 a wedding party of a friend delayed my going to the *observatory till nearly eleven o'clock. Doug had kindly offered to take the first part of the evening for me.*

As I entered the dome Doug greeted me with, "have you noticed that C2 is noisy?"

We discussed the data from the previous nights. Despite the apparent independent confirmation of my hunch about C2, I didn't feel any particular sense of relief, in fact almost the opposite.

Early the following week, during a break in the weather, I was able to reduce the data, plot the light curves and perform some Fourier transforms on the data. The case seemed secure. C2 was a variable star with a strong suggestion of several different periods, the dominant one being approximately 4.12 hours. But was it real? At Doug's suggestion a telex was sent to Breger in Austria inquiring if the other observatories had noticed anything unusual about C2.

The following day I hurried into the Physics department and asked the secretary if a telex had come from Austria. No, nothing. It was the end of the week and I probably wouldn't hear till Monday. Monday passed, then Tuesday, then the end of that week and still no news.

Now my nagging doubts began to blossom. Perhaps I had inadvertently insulted Breger by suggesting that one of the comparison stars that he had selected was variable itself. That was silly. More likely he had concluded that I was an incompetent observer and didn't bother to respond. Maybe he never received the telex.

February, and the international campaign, came to an end with still no word from Austria. I began to summarise the data and get it ready to send to Breger. The campaign had been, aside from the problem with C2, a spectacular success. Over 30 hours of excellent photometry had been collected at Devon and HD73756, the program star, showed clear evidence of multi-period variability. The comparison star C1 was constant to within a few millimagnitudes. I was very happy with the data, it

> *clearly showed that we could do high precision photometry from Devon but the anomalous behavior of C2 might jeopardize this notion. In my report to Breger I suggested that a short note should be published in the IBVS*(18) *concerning C2.*
>
> *Throughout March I was very busy with another star, 42 Persei, and with teaching classes. Despite this I was still puzzled about C2 but even more puzzled by the silence from Breger. Finally, at the end of March, with still no word from Breger and Doug's encouragement, I wrote a note to the IBVS in spite of my anxiety about the data. I also wrote to Breger and included a copy of the note to the IBVS. The words of Karl Popper: "those among us who are unwilling to expose their ideas to the hazard of refutation do not take part in the scientific game" were very real.*

Eventually I received a kind letter from Breger with an apology for not contacting me sooner and some encouraging comments regarding the variability of C2. Other observatories had corroborated my observations and Breger agreed that it probably was a variable star. In hindsight the case appears to be very simple yet it illustrates several aspects of personal science. Polanyi's comment:

> and even if you [the student] should succeed in carrying out an observation to check upon a statement of science and you found a result which contradicted it, you would rightly assume that you had made a mistake.(19)

is particularly apt. An observation in science must be accompanied by an expectation. In the case of C2 the expectation was simple, C2 is a UBV standard star and should not be variable.

My reluctance to accept the contrary of this expectation was real and discomforting. It spawned a sense of doubt, but not a Cartesian doubting upon which (according to the obectivist ideal) I could build indubitable knowledge. Rather, the doubt I felt was of a more visceral nature. It called into question initially my ability as an astronomer or the correct operation of our equipment, and possibly data collected in the past.

My initial reaction of doubt was a disciplined and conservative one. In a deliberately "Popperian" fashion I attempted to disprove the hypothesis that the variability I had observed in C2 was real. Even after I had accumulated a great deal of evidence, however, I continued to be doubtful and tenaciously clung to an erroneous view concerning the nature of UBV standard stars.

The last published research on C2, by Johnson, appeared in 1952(20) when it was placed on the list of UBV standards. Breger had, in a private communication, indicated that he had checked the star on several occasions and found it to be constant. The doubt I felt was reasonable given my apprentice's acceptance of the authority of acknowledged "experts". Yet that same apprenticeship had equipped me with the techniques of photometry and a tacit appraisal of my own work. Given the superb photometric conditions under which the observations had been made and my confidence in the photometry I had done on the other stars, I was led to the dissenting position that, in fact C2 is not constant but is a very low amplitude variable. This was bolstered by Doug's confidence that C2 was variable.

A more reasonable hypothesis concerning C2 is that it is a low amplitude, multi-period variable. Although Johnson could have detected this in 1952 it would have been at the very edge of detectability of his equipment and would have required a concerted effort to observe just C2. In his study, 150 stars were observed. There was neither enough time available nor sufficient inducement to look for variation such as this.

All of this points to a commonly acknowledged weakness of the naive falsificationist position on the testing of hypotheses. I was unable to reject the idea concerning the nature of C2 because of a strongly held presupposition concerning standard stars. Even after repeated observations refuted the idea that C2 was non-variable, I choose to doubt the observations themselves rather than the apparently discredited hypothesis. Presentations of science that attempt to develop the Popperian notion of **fallibilism** must guard against the mistaken simplification found in naive falsificationism (a view which Popper, himself, vigorously attacked(21)).

An example of how a naive falsificationist position is sometimes used as a portrayal of the scientific method and attitude is found in the popular high school physics text by Hewitt. Hewitt maintains that in order for a theory to be considered "scientific" it must

> conform to a cardinal rule. The rule is that the hypothesis must be testable. It is more important that there be a means of proving it **wrong** than there be a means of proving it correct.(22)

This is an obvious application of the naive falsificationist portrayal of scientific theory. To temper this view, David Bohm and F.David Peat counter that

> a new idea [theory] which has broad implications may require a long period of gestation before falsifiable inferences can be drawn from it. For example, the atomic hypothesis, first suggested by Democritus twenty-five hundred years ago, had no definitely falsifiable inferences for at least two thousand years. New theories are like growing plants that need to be nurtured and cultured for a time before they are exposed to the risks of the elements.(23)

Rather than placing undue emphasis on falsifiability, Bohm and Peat suggest the notion of "creative play" stressing both the role of confirmation and falsification in the emergence of scientific theory. These authors suggest that a dogmatic application of falsification stifles the creative growth of science.

A great deal of the doubt I experienced arose from my naiveté, my lack of experience. This is clearly brought out by the contrasting position taken by my supervisor, a more experienced astronomer. Our tacit appraisals of the situation were different. Regardless of one's sophistication, however, doubt remains as an active ingredient in the scientist's attitude. Doubt does not, however, function as a heuristic principle (ie, Cartesian skepticism or falsificationistic refuting as a means of securing knowledge). Rather, doubt exists in conjunction with commitment. Thus, the experience of doubting for the scientist is not conjured up at an appropriate point to act as a heuristic agent. Doubt arises when a situation exists that conflicts with an hypothesis that is embedded within a largely subsidiarily (tacitly) held presuppositional matrix. School science portrayals of the method of science via refutation will introduce a falsificationistic distortion unless they are tempered by an exploration of the presuppositions upon which the idea being tested is founded. Without such tempering, the impression can be too easily created that falsification acts as **the** scientific method rather than being part of a richer and more complex attitude that one could characterize as "scientific".

6.12 Conclusions

Uncovering one's personal science is a far from simple task. We dwell within the framework of our personal science and it is only through an interrogation of the at times mundane aspects of this indwelling that a sense of our personal science begins to emerge. Combing through one's personal engagement with science can provide numerous avenues by which one can begin to share with others. For a teacher of science this can be a vital connection with students. By exploring and at times sharing our personal science with students we begin, as teachers, to embody the ideas we teach. As Van Manen describes this:

> The way we stylize subject matter is a telltale expression of the way we hold it. We may possess a certain amount of information in literature, math or science, but only the knowledge we embody has truly become part of our being. A real English teacher tends not only to love reading, writing, and carrying poetry under one arm during coffee break; a real English teacher cannot help but poetize the world -- that is, think deeply about human experience through the incantative power of words.(23)

In the present chapter my research as an astronomer and a science teacher has been explored as a vehicle for uncovering personal science. In the next chapter it will be shown that the recognition of the personal dimension of science brings with it a shift in the epistemology of science teaching. It now becomes meaningful within the context of science education to encourage both students and teachers to explore their own personal science.

Notes Chapter Six

1. A beautiful example is found in Eiseley's book of essays The Star Thrower;(Wildwood House, London. 1978). In this book a number of Eiseley's essays deal with the apparent split between the natural and human sciences. It is Eiseley's intent to show that C.P. Snow's often quoted notion of the "two cultures" need not be considered normative to science. This is specifically brought out in his essay "The Illusion of the Two Cultures".
2. See Max Van Manen."Practicing Phenomenological Writing". **"Phenomenology + Pedagogy" 2(1)**, 1984, pp. 36-69.
3. In a different light, Valerie Suransky (now Suransky-Polakow), Phenomenology: An Alternative Research Paradigm and a Force for Social Change. **Journal of the British Society for Phenomenology, 11(2)**, 1980, pp. 163-178, explores the dichotomy between the natural sciences and the human sciences with respect (initially) to psychology. The paper broadens to encompass many of the issues alluded to in this proposal. See also: Valerie Polakow. "Whose Stories Should We Tell? A Call to Action".**Language Arts, 62(8)**, 1985, pp. 826-835.
4. "Practicing Phenomenological Writing", p.55.
5. Michael Polanyi.The Tacit Dimension. New York: Doubleday & Company, 1966, p.63.
6. Jerome Ravetz, Scientific Knowledge and its Social Problems, ppg 181-244, provides a useful discussion of the terms "fact" and "scientific knowledge".
7. Polanyi. Tacit Dimension. p.68.
8. Otto Friedrich Bollnow."On the Virtues of the Educator", in Education. A Biannual Collection of Recent German Contributions to the Field of Educational Research. vol. 20, pp. 69-79.
9. Levy, David.**Sky and Telescope, Vol 78. 4,** 1989, pp. 424, surprisingly, astronomy is ranked as the **seventh** most hazardous white collar profession.
10. See Hanson's Patterns of Discovery (Cambridge University Press, 1958) in which essentially a similar question is posed. Hanson then goes on to, over the next one hundred pages or so develop and then "debunk" the sense perception model of seeing. Hanson makes a very powerful case for the idea that all seeing is mediated by theory.
11. John Dewey. Experience and Education. New York: Collier Books, 1938, pg 17.
12. Paul Feyerabend.Science in a Free Society.London:Verso edition, 1982, p.11. Feyerabend uses the term dilettante rather than amateur, however his footnote would suggest that a serious amateur would also be considered as a dilettante.
13. Popper. Objective Knowledge. pp. 342-347.
14. An interesting discussion of the failure of science educators to clearly distinguish between the perception of scientists and the perception of students is provided by Willson, Victor L.,"Theory-Building and Theory-Confirming. Observation in

Science and Science Education". **Journal of Research in Science Teaching, 24(3)** pp. 279 - 284, 1987.

15. Stephen P. Norris. "The Philosophical Basis of Observation in Science and Science Education". **Journal of Research in Science Teaching, 22(9)**, 1985, pp. 817-833.
16. David Bohm and F. David Peat (1987). Science, Order and Creativity. Bantam Books: Toronto, pp. 45-46.
17. Polanyi. Personal Knowledge, p. 173.
18. **International Bulletin on Variable Stars.** This is a news bulletin produced by the International Astronomical Union that is used as a means of communicating quickly with other astronomers.
19. Polanyi. Tacit Knowledge. p. 64.
20. H.L. Johnson. **The Astrophysical Journal, 116**, p. 640, 1952.
21. Popper. Realism and the Aim of Science. pp. xxx - xxxv. In a 1982 introduction Popper explains at length the difference between his position and the naive falsificationist position he is accused of promoting.
22. Paul Hewitt. Conceptual Physics. pp 2 - 5. Although some useful ideas are introduced in this section the author, by simplifying the conepts, introduces a naive falsificationist position. Scientists simply do not consistently act as Hewitt claims they do, especially in the area of using only falsifiable hypotheses.
23. David Bohm and F.David Peat, pg. 59.
24. Max Van Manen. The Tone of Teaching. Richmond Hill, Ont.:Scholastic TAB; Portsmouth: Heinemann Educational Books, pg. 46, 1986.

Chapter Seven
Conclusion: The Educational Implications of Personal Science

7.1 Introduction

In previous chapters the central idea's of Michael Polanyi's theory of personal knowledge and Gerald Holton's thematic analysis of science have been used to give shape to what we now refer to as personal science. Many of the commonly accepted ideas of science education (the hypothetico-deductive method, the idea of detached objectivity, etc) have been criticized. In this, the concluding chapter of Part A of the thesis, the criticism of these ideas will continue but the emphasis will shift towards an exploration of how the ideas of personal science will influence both the epistemology and pedagogy of science education. We will begin with a discussion of school science and its epistemology. This will be followed by an investigation of the changing "epistemological center" implied by Polanyi's idea of tacit knowledge. The chapter will conclude with a discussion concerning the idea of indwelling and the growth of personal science as a practical concern of science education.

7.2 The Epistemology of School Science

The predominant epistemology of science education today is an empiricist-inductivist form of rationalism(1). In ~~very~~ broad terms this view posits that scientific knowledge - if it is to be knowledge at all - is independent of the knower and that it arises through the coordination of appropriate methods of science (observation, experimentation, theory testing, etc) and the valid application of logic. The many variant "species" of rationalism have been explored by, among others Smolicz and Nunan(2), and Nadeau and Desautels(3). Although the rationalism found in science education can run the gamut from "naive realism" (theories and their constructs are real and actual descriptions of reality) to instrumentalism (theories and their constructs are merely convenient fictions - useful in making testable predictions) some common manifestations of the rationalist epistemology (as summarized by Hodson[(4)]) in school science are:

> 1. Science, through detached observation, provides us with factual knowledge about the world.
>
> 2. Scientific knowledge derives directly from observation of phenomena.
>
> 3. Scientific knowledge is intrinsically neutral (value free).
>
> 4. Science uses reliable and objective methods to test its knowledge claims.

The intent of this thesis has not been to reject the entire rationalist program. It is however important, in light of Polanyi's critique of rationalism, to point out the potential (and actual) distortions that arise from the variant forms of rationalism as they appear in school science. It is also crucial to understand that the epistemology of science education cannot be isomorphic with the epistemology of science. This point is made strongly by Wilson and Cowell[(5)]:

> ... it seems clear that the importation [of ideas from philosophy of science] is often too hasty. There are, for instance, a number of questions (of, we suppose, really a semi-philosophical kind) relevant to anyone teaching science. How far should one be concerned with a certain form of thought ('scientific method'), as against a body of knowledge? What moral or psychological qualities are required for a good scientist? What is there about science which makes it important for everyone, and (in light of this) what sort of motivation should one seek to elicit from children? But what philosophers of science do is very far removed from, even if not totally irrelevant to, these concerns. Anyone who believed that what (say) Popper or Kuhn [or Polanyi] were concerned with was central to **education** in science would, surely, either not know the kinds of issues these philosophers were trying to tackle or not have a firm grasp on the idea of education.

The challenge facing us is to identify the excesses of rationalist epistemology within school science and use the ideas of personal science, where appropriate, to ameliorate these problems.

Consider, again, Hodson's summary of the four rationalist tendencies found in school science. First, in what way does science offer a detached observation of the world? My searching for rapid light variations in the star HD 32655 could hardly be described as "detached." Aside from the inherent contradiction of the term "detached" (how can I, the observer, be detached from my act of observing) the term glosses over - as inconsequential to science - the many motives and desires that animate me as an astronomer. Perhaps the term detached is intended to mean "honest." My search for rapid variability, in the end was futile. Honesty demands that I accept this. If, however, this is the sense of the meaning one ascribes to "scientific detachment" how can this be any different than the honesty one expects of the poet, engineer or store clerk? A harmful distortion of the rationalist programme, when adopted by school science, is the erroneous notion that science provides us with a special form of "truth." This exalts science to untenable heights and diminishes other modes of knowing.

Does science, as the second point of the rationalist epistemology suggests, derive directly from observation? Simple Gestalt experiments tell us how difficult it can be to see (or not see) a given pattern. Hanson, alluded to in the first chapter, has provided us with many delightful examples of this. In Chapter six, a friend's "discovery" that stars have color - after a lifetime of "seeing" - reminds us just how unreliable observing can be. While much of science involves observation of a "transparent kind", the previous chapters and stories help to underscore the theory-mediated nature of observing - especially in the context of making a scientific observation.

To counter the third claim of rationalism - that scientific knowledge is neutral - recall the lesson (Chapter Four) that Loren Eiseley learned from the yellow orb spider.

Our ideas are caught in a web - supported by more primitive thematic and paradigmatic notions which lie at the periphery of our thinking.

Consider the last claim that scientific truth emerges from objective methodologies. Despite persistent criticism of this overly simplified view of science, it continues to be offered to students (as well as being held by many teachers) as the essential aspect which characterizes science. Consider, for example the following quote from the 1988 edition of one of the most popular North American high school physics texts:

> To prove Aristotle wrong, Galileo developed a systematic method of observation, experimentation, and analysis. This method for studying natural events is known today as the scientific method. It is based on systematic experimentation with careful measurement and analysis of results ... Since Galileo's time scientists all over the world have used this method to gain a better understanding of the universe(6)

A quotation such as this obscures the real tension between Galileo and his Aristotelian contemporaries. Implicit in this passage is the suggestion that Aristotle had no method or at best an ad hoc and chaotic one. This is patently false and misses the essential point that acceptance of the Galilean view of physics came through a sweeping change in vision. The Aristotelian physics was part of a unified system embracing all of thought and experience. Galileo's programme was far less ambitious and rested on a view of a science devoted to detailed measurement of small, isolated phenomena - something unintelligible to Aristotelians. It is a very dubious claim that Galileo proved Aristotle wrong. The questions deemed important to Aristotelian scientists were much different than those considered by Galileo. The clash between Aristotelian and Galilean science should be used to point out to students the vital role that worldview and philosophy play in science rather than act as an object lesson for the virtues of "good scientific method."

While careful experimentation and analysis are indeed vital aspects of science and should not be devalued, the unqualified appeal to a universal scientific method is a parody of science and conveys little of the richness and intellectual challenge of science. If students are to begin to acquire a sense of their own personal science it is incumbent upon us to let them see beyond the external trappings of scientific methods. When I look at the light curves for the delta-Scuti star KW 207 I "see" beyond the mere dots strewn along the page. I am reminded of the bitterly cold February nights and the sense of personal satisfaction I felt when I had finished one particularly long night of observing. I remember the sense of doubt caused by a standard star that was variable and my relief when others confirmed this fact. All of this and much more - my narrative - lies hidden under the formal presentation of the "facts." The stories in Chapter six help to establish a bridge between the formal and the personal dimension of the astronomy that I do.

The problems posed by too much attention to the methods of science have been commented on by numerous authors. Entwistle(7) and Duckworth, and Brush(8) suggest that the notion of impersonal scientific method coupled with the rationalistic ideal of value-free scientific knowledge has been a major factor in the declining enrollment of students (especially females) in the sciences. They have argued that a more human centered view of science would improve the recruitment of young people into science courses.

Rationalist epistemologies - especially empiricism - tend to view the acquisition of knowledge as a process of accumulation. Working from this position, the mind is seen as a **tabula rasa** and leads to what was described in Chapter Two as the **bucket theory** of science. The prevalence and persistence of the bucket image as the epistemology of science education has been well documented. Gordon(10) suggests that it forms part of the hidden curriculum of science education and it is a view which is acritically accepted by many educators. The structure of curricula, the methodologies of instruction and the techniques of evaluation are saturated by this philosophy. For the vast majority of students science is a purely cognitive exercise. (A good summary of this is found in the Science Council of Canada study: **Science**

Education in Canadian Schools(11).) In the end, Gordon concludes that the empiricist-inductivist epistemology leads the student to a state of "gross misinformation about science" and results in a technological consciousness that is either scientistic (un-critically accepting of science and technology) or "anti-scientistic" (un-critically rejecting science and technology).

Not only does the rationalist programme distort science - it also appears to be an ineffective epistemology for science education. This point is raised by Fensham(12) in a discussion of the implications of research concerning the nature and longevity of what are termed "alternate conceptions" in science. (Other researchers use the terms misconception or alternative frameworks.) An alternative framework is said to exist in a student when both a conceptual frame, conflicting with the "correct" scientific view, and the scientifically correct view are held simultaneously. For example, high school and college students will often appear to hold both Aristotelian and Newtonian notions of force and motion at the same time. Under "normal" classroom settings the students will give the "correct" response but when faced with novel situations or persistent questioning they will revert to Aristotelian notions of force and motion (see McDermott(13), and Champagne, Klopfer and Anderson(14)).

There is a wealth of research conducted over the past two decades that demonstrates both the existence of identifiable alternative conceptual frameworks and their remarkable resistance to change through teaching (see Thijs(15) et al. for a recent review of this area). The tenacity of student alternative concepts calls into question the empiricist-inductivist epistemology of school science and the instructional strategies that emerge from that epistemology.

According to Fensham(16), the most common instructional sequence identifiable in science education fits the following schema:

Learner + Instructional Input --> Intended Outcomes

Such an instructional sequence is a sensible application of an empiricist-inductivist epistemology; knowledge consists of separate bits which are transferable to students via instruction (hence not far removed from Locke's tabula rasa). In light of research into students' alternate frameworks, Fensham(17) concludes:

> ... more recent studies have led to a growing volume of findings that require us to question assumptions about the basic process of science teaching. The findings to which I refer are not all novel or recent [circa 1983]. Indeed they (or their like) must have been available to generations of teachers who were prepared and able to listen to their students.

In the following section it will be argued that the epistemology of science education is among the assumptions of science teaching in need of questioning. In particular it will be shown that an epistemology built around the central notions of personal science may well prove more effective in bridging the conceptual chasm sometimes separating students and teachers and that the introduction of the idea of personal science may avoid some of the distortions ascribed to the rationalist epistemology of school science. A conclusion that emerges from this research is that there is a strong affinity between the ideas of personal science and the constructivist approach to science teaching.

7.3 Personal Science and its Relation to Constructivist Models of Science Education

During the 1970's Piagetean theories of developmental stages were explored and applied to learning in science and became the groundwork from which **constructivist** (or **generative**) theories of learning were developed. Central to these learning theories is the recognition of the active part that the learner plays in constructing knowledge. Exemplars of this movement are Osborne and Wittrock(18), Gilbert, Osborne and Fensham(19), Shayer and Adey(20), Driver(21), Pines and West(22) and Driver, Guesne and Tiberghien(23). Concepts such as **children's science** or **the pupil as scientist** began to emerge and were used to give flesh to the notion that a learner is engaged in a dynamic of making sense of a given educational situation. Holistic ideas such as **conceptual ecology**(24,25) were employed in which a student, utilizing networks of existing knowledge, beliefs, experiences and world view, attempts to assimilate new knowledge into this rich superstructure. A key tenet of contructivism is that the acquisition of meaningful knowledge always entails active construction or generation of meaning by the learner. Constructivists make a distinction between private understanding and public knowledge(26). The statement of a fact, for example may demonstrate the acquisition of public knowledge but not necessarily imply private understanding of that knowledge in any integrated sense. This is in essence the same as Ausubel's distinction between rote and meaningful learning. The overarching concern of contructivism is how students acquire and apply conceptual understandings of large bodies of public knowledge. A closely related concern centers around the alternate conceptions discussed previously as well as the phenomenon of conceptual change in students.

The question of how students acquire concepts or experience conceptual change is a very broad one. David Stenhouse(27), in addressing this question, advances the conclusion that teachers must become more adept at using philosophical ideas in understanding the nature of their own conceptions as well as those held by their students. In particular he suggests the use of **language-game**s(28) as the philosophical tool through which concept construction and change may be understood and nurtured. Borrowing from the later philosophy of Wittgenstein, the idea of **language-games** is that meaning of words cannot be divorced from the use of those words. We learn the meanings of words through participation in language games, the rules of which can never be exhaustively known and which, themselves, change through use. Language and its understanding takes on an inter-subjective nature in Wittgenstein's philosophy. Leading a student to conceptual change requires that the teacher and student engage in an exploration of **each other's** language-games and that the student will construct a new language-game more closely in line with that of the teacher. Understanding a concept anew entails learning an expanded or different set of rules for the valid application of that concept. This is a decisive move away from the empiricist model of learning for it now implies an essential inter-subjective communication of student and teacher language-games. It is not an unfair extrapolation to suggest that teachers would also benefit from an exploration of their own sense of personal narrative (personal science) as well as that of their student's. A story, such as the one which opened Chapter four could serve as a "meeting place" for the teacher and student narratives and could help provide a context in which a conceptual language-game could unfold.

Stenhouse's position is very similar to the one developed by Hugh Munby(29) in the discussion paper "What is Scientific Thinking" in which the idea of intellectual dependence is introduced. By not honoring the language-game interaction of student and teacher the student is made un-critically dependent on the teacher. A simple yes-no type of answer is not intelligible within the science lesson language-game of the student (although it is perfectly clear what yes-no means within the student's teacher-student relation language-game). This prevents the student from acquiring the necessary rules of use to affect a successful conceptual change.

Another attempt to delve into the origin of student conceptions is due to Andersson(30) who introduces the phrase **"experiential Gestalt of causation"**. Through our experience of the world we intuit, for example, relationships between force and effect. A large "push" may result in a large effect on an object; we can affect a greater change on an object close at hand than one farther away, etc. Our experience gives shape to our expectation of how we will continue to interact with the world and to prefigure our notion of causation - hence an experiential Gestalt of causation.

The language-game application of Stenhouse and the experiential Gestalt of Andersson imply a strong convergence towards Polanyi's idea of the **from-to** structure of knowing. Contained within the from-to structure is the tacit understanding that a student holds of a given situation or concept. This tacit understanding subsumes both Andersson's experiential Gestalt and the language-games to which Stenhouse alludes.

In case of the acquisition of a Gestalt, we are for the most part only subsidiarily aware of the countless sensory impressions that continuously bombard us. Among these impressions we may detect patterns. Such patterns may be as simple as noticing that releasing a toy and the falling of the toy are causally connected. Or we may see clearly that a piece of feather floats to the ground while a rock falls quickly. These patterns were noticed early in life and woven into our tacit awareness of the world. Polanyi has also shown that much more subtle patterns can be tacitly perceived and incorporated into our Gestalt of the world. For example, in an experiment by Lazarus and McCleary(31), subjects were presented with series of nonsense syllables. After some of the syllables the person was subjected to an electric shock and soon began to show signs of anticipation of the shock when presented with the appropriate nonsense syllable. When questioned, however, subjects were unable to identify those syllables which preceded electrocution. Lazarus called this **subception** and it was seen by Polanyi as a "striking example of tacit knowing." In a similar way, then the **experiential Gestalt of causation** described by Andersson is subsumed within Polanyi's more fundamental notion of tacit knowing.

Polanyi devotes a great deal of space in Personal Knowledge to a discussion of language and the role that the tacit dimension plays in acquiring the rules of language. Although Polanyi was suspicious of Wittgenstein's notion of the language game(32), C.B. Daly(33), by juxtaposing passages from Personal Knowledge and Wittgenstein's Philosophical Investigations, demonstrates the similarities between Polanyi's understanding of the tacit acquisition of the rules of grammar and Wittgenstein's use of the language-game. In doing this we see that the language-game may be seen as a natural application of Polanyi's view that our explicit knowledge is grounded in the tacit. By learning the expanded set of rules governing the new conception (ie. the superior or scientifically accepted conception) the student's language-game has been modified. So too has the student's tacit understanding of the concept and we may invert this to say that in order to affect a conceptual change, the student - so that he or she may comprehend this new conceptual understanding - must possess the necessary tacit knowledge to make the from-to structure of knowing the new conception meaningful. As Polanyi puts it:

> ... no meaningful knowledge can be acquired, except by an act of comprehension which consists in merging our awareness of a set of particulars [for the most only tacitly known] into our focal awareness of their joint significance.(34)

The constructivist hypothesis that the child is an active builder of his or her worldview finds a natural anchor in Polanyi's epistemology of personal knowledge and leads to the conclusion that a more appropriate epistemology for science education is one that is centered in the person rather than in the empiricist-inductivist ideal of detached impersonal knowledge. Under this new epistemological focus, school science must be grounded in the student's own personal science.

7.4 Science Education Centered on Personal Science

In the previous two sections it has been argued that an epistemology of science education founded on the rationalist ideal of impersonal detached knowledge is flawed. This leads to one of the central themes of this thesis - that science education must broaden its epistemological scope to acknowledge the personal dimension of knowing.

The recognition that tacit knowing exists in its **from-to** structure is cited by Marjorie Grene(35) as Polanyi's truly unique and original contribution to philosophy. This point is expressed by Polanyi as:

> ... tacit knowing is the dominant principle of all knowledge, and ... its rejection would, therefore, automatically involve the rejection of any knowledge whatever. ... the knower shapes his own knowledge ... both at the **lowest levels** of knowing and in the **loftiest achievements** of the human intelligence ...(36)

For the educator the task becomes one of designing methodologies and curricular objectives that honor the personal dimension of knowledge. This point was made two decades ago by Harry S. Broudy:

> It is my hunch that these anomalies [ie. the failures in behavioral learning theories to account for non measurable aspects of learning] are bound to plague us as long as we insist on ignoring or belittling the tacit element in the uses of school learning.(37)

A similar point has been made more recently by the philosopher of education, Jeffrey Kane(38) as well as by David Stenhouse(39) in his observation that "Polanyi's notion of the 'tacit dimension' is of immense importance for education, and less recognized than it should be."

A curriculum that valued the tacit dimension of knowing would invest energy in anticipating and developing the subsidiary (tacitly held) background required for the student's assimilation of new ideas and **it would do so without the expectation that all learning need be measurable**. This would be facilitated by attending to the notion of the inherent **richness** of science which was developed in chapter two.

Knowing possesses a from-to structure inextricably bound with the learner. Simply telling or showing a concept to a student without first considering the subsidiary antecedents to the idea makes little sense. As an example consider the conversation (described at the beginning of the first chapter) that I held with my daughter Leah over what we both saw through her spectroscope. That Leah saw something different than I did should not have surprised me. The very act of looking is hardly as transparent as naive empiricism would suggest. Leah's only exposure to spectroscopy came via a few illustrations of **continuous** spectra found in her school book. In our discussion that followed I learned that Leah and her classmates did very little in the way of simple "hands on" experimentation in the science unit on light. This was disappointing, especially since she had been dutifully memorizing the optical layouts of various optical instruments (without actually seeing the instruments in front of her) and learning numerous definitions.

Later, when going through Leah's notes, I was struck by two things. First, the presentation was very abstract with little to relate light to things around the home. Second, the notes were beautifully illustrated and colored. This same pattern persisted throughout the entire year's notes. It seems clear that the activities which provided the greatest satisfaction (drawing and coloring) were at best considered incidental to the science. Very little was done to develop the subsidiary understandings Leah would need to more fully assimilate the ideas written down. What was missing in the unit was richness - both in content and delivery. Leah's clear enjoyment of illustration could have been used as a vehicle to **draw** rather than **define** some of the ideas to which she was being introduced. The formation of an experiential Gestalt would be fostered by having her perform activities and then describe the results. The description could be in the form of written discourse but also as annotated drawings. As we saw in Chapter four, Martin(40) and Miller suggest the use of story as a practical means by which students may participate in the science they are learning. At this stage of science education, more emphasis should be given to the place of observing and participating bodily in the science. Perception and Gestalt acquisition play a prominent role in Polanyi's epistemology.

Polanyi notes that a child learns the meaning of a word through sustained imitation of the way in which adults use that word, in many different contexts - spoken as well as written. He later extends this to become the kernel of all learning activities:

> Each word must be noted in a number of contexts until its meaning is roughly grasped; it must then be read in books, and used for some time in speech and writing under the guidance of adults in order that its most important shades of meaning be mastered. This training can be supplemented by precept, but imitative practice must always remain its main principle. The same is true of the process by which the elements of the higher arts are assimilated. Painting, music, etc., can be learned only by practice, guided by intelligent imitation. And this applies also to the art of scientific discovery.(41)

In coming to the curriculum, the teacher must be aware of the diversity of ways in which a specific objective can be presented to the student as well as carefully mapping out(42) what he or she (the teacher), through an act of professional judgment, considers to be the important antecedents to the objective. These antecedents will form the subsidiary background for the student through which a given objective will be encountered.

For the young student (elementary school) the principal objective of the science curriculum may well be heavily weighted in the direction of cultivating the personal science of the student. In Leah's case, a diminished emphasis on the cognitive (ie. definitional, factual, etc.) and more emphasis on a multifaceted experiential encounter with the objectives of the unit on light may prove more appropriate in presenting science to the student. It is only **through** a rich subsidiary background that the more formal aspects of the science can begin to make sense. As the student matures the diverse aspects of science discussed in Chapter Two will begin make their demands on the student but at all levels learning will still conform to the **from-to** structure of personal knowing and hence attention to the personal science of the student will persist.

As an example of these ideas, consider the presentation of one of the simplest topics in the high school physics curriculum - uniform motion. Four high school textbooks used in Canadian and American schools have been examined. The texts are: A: Physics: Principles and Problems(43) (Murphy et al.), B: Physics: A Human

Endeavour(44) (Paul, Pierce and Stief), C: PSSC Physics(45) (Haber-Schaim, Dodge and Walter) and D: PhysicAL: An Activity Approach to Physics(46) (Martin and Spronk). In the first three texts (A,B,C), uniform unaccelerated motion is presented as self evident and the principal burden of the early parts of the respective chapters on motion consist of acquainting the student with the correct mathematical treatment of uniform unaccelerated motion. The emphasis then progresses to a treatment of accelerated motion and the appropriate mathematical techniques needed to describe acceleration.

This is a straightforward and traditional way of presenting motion. It has an appeal of clarity and logic that may seem unassailable. In the first three texts some space is devoted to worked examples and problems but no formal experimentation occurs in exploring the idea of uniform unaccelerated motion. Textbook D, however, reverses, to some extent, the order of presentation. Students are first asked to examine falling motion and it is only toward the end of the chapter that the concept of uniform unaccelerated motion is introduced. The rationale for such an order of presentation is simply that the uniform unaccelerated motion of school texts does not occur in nature and hence cannot be assumed to be self evident. Instead, the most natural of all motions - falling - is considered first. This type of motion is already part of the student's experiential Gestalt. As well, it is only after doing five experiments (if the text is followed) and several activities on falling and other forms of accelerated motion that the concept of uniform unaccelerated motion is introduced. Thus, natural falling motion, which encompasses both accelerated and unaccelerated motion, is seen as a necessary antecedent to the abstract idea of uniform unaccelerated motion(47) and its introduction serves to develop the subsidiary set of ideas needed to grasp the more abstract idea of uniform unaccelerated motion.

Personal science - rooted in the **from-to** structure of knowing - is operative at all stages of the student's career and forms the fundamental point of interaction of the student with the science being taught. The recognition of the tacit dimension of knowing represents a fruitful and promising direction for the epistemology of science education and rests on the realization that:

> While tacit knowledge can be possessed by itself, explicit knowledge must rely on being tacitly understood and applied. Hence, all knowledge is either tacit or rooted in tacit knowledge.(48)

7.5 Indwelling and the Growth of Personal Science

In Chapter Three it was suggested that indwelling is the locus of all meaning in Polanyi's epistemology. The idea of indwelling was extended beyond the simple bodily interiorization of a tool, such as a hammer or a walking cane, to include skills and the employment of scientific theories and other modes of thought. Within Polanyi's theory of knowledge we see an incorporation of, at one time explicitly held knowledge, into a tacit level fabric of knowledge. One of the examples used by Polanyi to develop this point is his discussion of learning to drive an automobile:

> We can watch the process by which an explicit prescription becomes increasingly effective as it sinks deeper into a tacit matrix. Take a manual for driving a motor car and learn it by heart. Assuming you have never seen a motor car, you will have to identify its parts from the illustrations of the manual. You can then sit down at the wheel and try to carry out the operations prescribed by the text. Thus you will start learning to drive and eventually establish the bearing of the manual on all the objects it indicates and the skills it teaches. The text of the manual is shifted to the back of the driver's mind, and is transposed almost entirely into the tacit operations of a skill.(49)

The skilled driver has interiorized -or dwells in - the text of the manual. Although this example describes a common, albeit highly complex skill, it is attractive to consider it as an analogy to science education itself. Consider how the analogy might unfold.

At first, the student's only contact with an idea from science may come in the form of a textual account. Just as in the previous case, the student may not have "seen" the science beforehand. (For example, how often does a student learn the principles of operation of a machine such as a mass spectrometer with out actually seeing the device?) Eventually, however, the student must put into practice the ideas being considered - the student must actually "drive" - and as this active participation in the ideas progresses, focal awareness of the particulars themselves (scientific skills, ideas and principles) shifts more and more to the tacit level of awareness.

The student, by dwelling in the ideas of science enlarges his or her tacit understanding along with an increase in explicit knowledge. Indwelling, then is the vital process by which knowledge is incorporated into the knowing mind and this is a point missing in the rationalist epistemologies prevalent in science education today. The persistence of student alternate conceptions in the face of formal teaching makes sense from the vantage point offered by the ideas of tacit knowledge and indwelling. That the student holds alternate conceptions and that these conceptions form a matrix from which intuitions, hunches and guesses arise demonstrates that the student is, indeed, dwelling in his or her ideas. Recall the comment from Polanyi used in the previous chapter:

> When we accept a certain set of pre-suppositions and use them as our interpretive framework, we may be said to dwell in them as we do in our own body. ...
>
> It is by his assimilation of the framework of science that the scientist makes sense of experience. This making sense of experience is a skillful act which impresses the personal participation of the scientist on the resultant knowledge.(50)

What needs to be questioned here is to what extent, if at all, do we allow students to dwell in the ideas of the science? At stake in this question is the extent to which we allow students to establish a sense of "ownership" in the ideas of science. In outlining his new objectives for science teaching, Fensham states that:

> Acknowledgment of the world views science students bring to their science classroom is a major basis for the new types of objectives for science education(51)

Fensham's acknowledgment should be augmented to include a recognition of the importance that tacit knowledge and indwelling can play in establishing a basis for science education. This last point is supported by Sternberg and Caruso who write that:

> ... tacit knowledge is an essential form of knowledge for success, both among children and among adults. It differs from direct knowledge and mediated knowledge primarily in the locus of the instructor, which is the individual doing the learning rather than an other who serves, directly or indirectly, as teacher. Much of one's successful performance in everyday functioning can be traced to the acquisition and effective activation of tacit knowledge.(52)

A question still remaining is which students need to "indwell"? If indwelling truly is the locus of all meaning and if meaningful (as opposed to rote) learning is the goal we strive toward then the answer must be, all students need to indwell. In fact it can be argued that students do indwell and that the failure of some students to experience a conceptual change, for example, is a tacit recognition by the student that the ideas being offered have not been made relevant to the constructed worldview of the student. Indwelling comes in many diverse ways. For some students, reading a play such as Golding's The Brass Butterfly(53) or Ibsen's Enemy of the People(54) may allow the indwelling of science and society or science and technology ideas to occur. The student who is an avid hunter could be challenged to write about his or her avocation with respect to the topics in an ecology or biology class. Suggestions such as these may seem to be common places of good teaching but they are more than that. Ultimately, such examples rest on a recognition of the fundamentally personal nature of knowledge. An "indwelling education" would not do away with, in a radical sense, many of the traditional concerns regarding content and rigor. It would however recognize the essential role of the tacit dimension of knowing and the need to create a rich subsidiary environment making a meaningful acquisition of ideas possible.

7.6 A Society of Explorers

How then are we to effectively encourage the acquisition of tacit knowledge and indwelling within the confines of science education? How can we foster the development of a personal science within the student? For Polanyi, whose principal concern was the theory of knowledge and not educational theory, indwelling and the growth of a rich substructure of tacit knowledge was the natural state reached by a scientist through a long process of formal (school) training and apprenticeship as both a graduate student and a younger colleague of more experienced scientists. This has significant implications for the relationship between the student and the teacher for it implies a shift in the role of the teacher. The student and the teacher become part of what Polanyi described as a "Society of Explorers"(55) and in the words of Richard Gelwick:

> Perhaps no other phrase so aptly encompasses the importance of Polanyi's investigations as "a Society of Explorers." It suggests both the centrality of discovery and the comprehensive significance of his philosophy. It pictures the intense effort of the individual pioneer who makes the great breakthrough. But it also images the social roots and ties that surround the seemingly individual triumph.(56)

The teacher is now a representative of a rich and historically rooted tradition. It is the visible participation of the teacher in this tradition that is of importance here. Studies on the attitudes of students towards science (Shibeci(57), 1986; Koballa & Crawley(58), 1985; Brush(59) 1979) indicate the importance of the teacher's role as exemplar in the transmission of an image of science to the student. For Polanyi the role of the teacher goes deeper than this.

> [It is] the combined action of authority and trust which underlies both the learning of language and ... the whole transmission of culture to succeeding generations. ...
>
> The assimilation of great systems of articulate lore by novices of various grades is made possible only by a previous act of affiliation, by which the novice accepts apprenticeship to a community which

> cultivates this lore, appreciates its values and strives to act by its standards.(60)

Polanyi's theory of knowledge necessarily implies that all knowledge has a presuppositional nature -it is embedded within a tradition. The transmission of this tradition cannot be completely explicit and it is the task of the teacher to model this tradition. Thus, the teacher's disposition towards science not only impinges on the attitudes of his or her students, it also provides a context in which to develop and explore the ideas of science. In Heidegger's words:

> Teaching is more difficult than learning; for only he who can truly learn -and only as long as he can do it- can truly teach.(61)

When I share my passion for astronomy with my students I am doing more than communicating astronomy to them. I am signifying that I am a fellow traveler and fellow learner with them. Almost always this sharing will come in the form of story - brief anecdotes. It should be added that I am not suggesting that the teacher must be a scientist. I do maintain, however, that the science teacher who values the notions of personal science and indwelling must have a sense of story to tell. That teacher must hold a genuine relationship with and a passion for the science he or she seeks to teach.

Within the shifted epistemological center implicit in personal science the teacher is no longer the "dispenser of knowledge", just as the student is no longer the "passive, receptacle of knowledge." The teacher, by dwelling within the ideas which he or she also hopes to share with the student, helps create for that student the necessary conditions for the formation of "trust" . and a personal allegiance to those ideas. According to Polanyi

> The learner, like the discoverer, must believe before he can know. But while the problem-solver's foreknowledge expresses confidence in himself, the intimations followed by the learner are based predominantly on his confidence in others ...(62)

The teacher and the student become explorers together, sharing a common purpose. Along the way the teacher, by virtue of experience, faces the pedagogic challenge of providing for the student curricula that make sense within both the tacit and articulated framework of the student as well as pointing the student to questions that will enlarge his or her framework.

7.7 Some Conclusions and Future Avenues of Research

A key ingredient that can be distilled from Polanyi's analysis of science is the role that active participation, on the part of the student, plays in the emergence of personal science. Another important point in Polanyi's thinking about science can be subsumed under his notion of **intellectual passion**, an idea which is pursued at considerable length in Personal Knowledge(63). It is through indwelling that a sense of intellectual passion emerges and embraces, among others, notions such as judgment, beauty and simplicity in science. If all students, not only those who eventually become scientists, are to begin to understand science more completely then the idea of indwelling as an essential part of the epistemology of science education must be attended to.

The ideas presented in the previous chapters have raised some significant challenges for science education that, if heeded, will have impact on teachers and students. A clear message that unfolds for teachers is the vital role that one's personal science can bring to bear on how you, as teacher, represent a particular subject to your students. An important part of the manifestation of personal science comes through a sense of story or personal narrative. Simply put, teachers must have stories to tell that are cogent and honest evidence of a lived experience with the ideas they hold before their students. In Chapter Six the story, "Midnight Conversations With Tom", challenged me to consider which orientation - that of the professional or that of the amateur - would I want to pass on to my students. Such either-or questions are often inherently flawed, creating a false dichotomy where there is none. Both Tom and I stood outside on a cold January night, fundamentally, because of a deeply personal sense of enjoyment and participation in the stars.

Tom has, in the few years since the story was written, decided to become a teacher. Soon he will stand before a classroom full of students. It is extremely difficult to say whether or not this individual will become an exemplary teacher. The technical demands of teaching - aside from its personal aspects - are considerable. However, assuming Tom acquires all the requisite skills needed to become a "competent" teacher, one more point must be addressed. It resolves into this: will Tom's view of epistemology, of the nature of science teaching, enable him to see the valuable role his personal love of astronomy can play in teaching? Without a formal valuing of the personal dimension of knowing and the importance of one's own sense of story as well as those of student's, the ideas of personal science will not significantly influence science education.

One way, then, in which the ideas explored in this thesis can be applied is to introduce them to student teachers. As part of their practical training, student teachers should be encouraged to explore their own narratives and to uncover the sense of their personal science. Within their training, science teachers should be introduced to the diversity of science discussed in Chapter 2 and the role that the personal dimension of knowing plays in science.

Another way in which the ideas developed in this thesis could influence science education would come through a recognition, on the part of teachers and curriculum planners, of the tacit dimension of knowing. In developing curricular objectives attention should be given to the anticipated tacit level understandings necessary for the acquisition of that objective. To borrow the terms used in Chapter 4, our teaching methodologies should address both the narrative and paradigmatic modes of knowing.

Learning of a principle or concept should be seen in broader terms and engage more than the purely cognitive aspects of learning.

There are a number of research questions that flow from the present work. One such question would center around the perception, by science teachers, of their personal narratives of science. To what extent do teachers make use of their own stories and how do they view themselves with respect to their disciplines? Do teachers possess a sense of personal science?

A related question focuses on the nature of children's stories about science. To what extent, if at all, do children possess a sense of story that can be related to their experience of school science.

The suggestion has been made that Polanyi's theory of personal knowledge and the ideas developed in this thesis provide a natural philosophical anchor for constructivist models of learning. Such a claim warrants further study. Can, for example, a richer understanding of the tacit dimension of knowledge lead to insights into the nature of conceptual change and ultimately provide insight into how to better enable students to make such changes?

At the present time, science curricula are under increasing pressure to address Science-Technology-Society (STS) issues and to "meet the needs" of a wider cross section of students. How will teaching methodologies change to accommodate such diverse needs? A fruitful area of exploration would be to consider the extent to which the narrative mode of knowing could be used to achieve these curricular goals.

A question which emerges from this study is the extent to which my stories of science bear similarity with the experience and stories of other scientists. Would, for example the stories "Satisfaction" or "Doubt" resonate with the experience of a chemist or archaeologist? Can the narrative mode of knowing provide us with a means to more fully explore the personal dimension of science?

7.8 Some Personal Reflections on the Research

B.F. Skinner wrote that "science is the destruction of mystery." Such a comment saddens me. It robs science of its humanity and, ultimately makes science impossible. Science can exist only in recognition of the mysterious universe of which humanity is part. Science, for many, has lost a sense of the poetic. It has become utilitarian and narrow in scope and parochial in curiously sophisticated ways. Yet if one reads with care the reflections of the masters of science and accomplished scientists such as Michael Polanyi and Loren Eiseley, one discovers a sense of reverence. In the essays "Science and the Sense of the Holy(64)" and "The Illusion of the Two Cultures(65)", Loren Eiseley tackles head-on the divisive view that drives a wedge between science and the humanities. I have often been struck by the terrible dilemma this false dichotomy creates for science educators. For, we seemingly must straddle an ever widening gulf. On one side we see the human needs of our students and on the other the requirements of our discipline. I side with Eiseley and hope this thesis will, if only in a small way, contribute to the explosion of the myth that the sciences and the humanities are fundamentally at odds with each other.

Notes Chapter 7

1 Rationalism used in this sense subsumes both empiricist and rationalist traditions and should, perhaps be called **scientific rationalism.** This is consistent with the view developed by Bronowkski and Mazlish in The Western Intellectual Tradition, (New York: Harper and Row, 1975), pp. 491-493. This view is also closely aligned with the modern philosophy of **logical analysis**; see Bertrand Russel's A History of Western Philosophy, London:Unwin PaperBack edition, 1984, pp. 783-789.

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32 Polanyi rejects Wittgenstein's language game notion when, on pg. 113, Personal Knowledge, he writes:

The understatement that language is a set of convenient symbols used according to the conventional rules of a 'language-game' originates in the tradition of nominalism, which teaches that general terms are merely names designating certain collections of objects - a doctrine which, in spite of the difficulties admittedly attached to it, is accepted today by most writers in England and America, in abhorrence of its metaphysical alternatives.

Polanyi's reaction appears to be directed to the early writings of Wittgenstein and are not a fair treatment of the later Wittgensteinian idea of the language game.

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40. K. Martin & E. Miller. "Storytelling and Science." **Language Arts, 65(3),** pp. 255-259, 1988.

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42 Such mapping is very similar to the conceptual mapping scheme of Novak and Gowin with the exception that it is now seen as a tool to be used by the teacher to enhance the tacit awareness of the student. See: Novak and Gowan, Learning How to Learn, Cambridge:Cambridge University Press, 1984.

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44 Douglas Paul, Denny Peirce and Kenneth Stief. Physics: A Human Endeavour. Toronto: Holt, Rinehart and Winston of Canada, 1973, pp.8-31.

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46 Brian Martin and Neil Spronk.Physical: An Activity Approach to Physics. Edmonton:J.M. Lebel Enterprises, 1989, pp.1-25.

47 The idea of uniform unaccelerated motion should not be confused with the naive concept that students have of motion - although this would seem to be commonly done. Students often conjoin naive ideas of movement with force which is perfectly reasonable within their experiential gestalt (ie, by pushing you can keep an object moving at the same speed). The scientific conception of motion is not inherent in this naive conception and can only be assimilated by the student when, in Polanyi's terms, it becomes intellectually more satisfying to separate force and motion and to understand uniform unaccelerated motion as a distinct aspect of motion.

48 Michael Polanyi. The Tacit Dimension. Garden City: Doubleday & Company, 1967, pp. 95-96.

49 Polanyi, Knowing and Being, p. 144.

50 Polanyi, Personal Knowledge, p.60.

51 Fensham, p. 6.

52 Sternberg and Caruso, "Practical Modes of Knowing", in Learning and Teaching the Ways of Knowing: Eighty-fourth Yearbook of the National Society for the Study of Education,(part II). Elliot Eisner (ed.), Chicago: University of Chicago Press, 1985, p. 150.

53. William Golding.The Brass Butterfly.London:Faber&Faber, 1958.

54. Henrik Ibsen. An Enemy of the People from The Complete Major Prose Plays, North American Library, New York:Times Mirror, 1978.

55. Michael Polanyi. The Tacit Dimension, p. 91.

56. Richard Gelwick. The Way of Discovery, p. xi.

57. R.A. Shibeci."Images of Science and Scientists and Science Education".**Science Education, 70(2)**,139-149, 1986. In this article the author concludes that positive image (ie, a more human portrayal of science and scientists) can be achieved. He cites the Harvard Project Physics curriculum as an exemplar of a science program having demonstrable positive impact on the attitudes of students towards science.

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59. L. R. Brush."Avoidance of Science and Stereotypes of Scientists".**Journal of Research in Science Teaching, 16**, 240-241, 1979.

60. Personal Knowledge, p. 207.

61. Martin Heidegger (1977).Basic Writings. ed D.F.Krell, Harper & Row: New York, pg. 251.

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Part B

Astronomical Investigations

(Chapters 8 - 10 comprise the second major part of this study and provide detailed discussions of the astronomical research mentioned in the previous chapters of this thesis.)

Chapter Eight
The Ellipsoidal Variable 42 Persei: Observations and Model

8.1 Introduction

The latest edition of the General Catalogue of Variable Stars lists the star 42 Persei (= HR 1177 = HD 23848 = V467 Per, $\alpha(2000) = 3^h\ 49^m\ 32^s.6$, $\delta(2000) = 33°5'29"$) as a single-lined eclipsing variable with a period of $22^d.58$. This datum is based on photometry reported by Kolykhalova(1) and is in marked disagreement with the radial velocity data analyzed by Morbey and Brosterhus(2) who supplied orbital elements for the system and concluded that the period of 42 Persei is $1^d.765346$. Following the suggestion of Batten(3), who showed that the photometric data can be phased with the short spectroscopic period, and that it is suggestive of ellipsoidal variability, we have placed 42 Persei on our observing program of suspected ellipsoidal variables. Photometry carried out from January 1988 through March 1989 supports the orbital period given by Morbey and Brosterhus and confirms that 42 Persei is an ellipsoidal variable star system.

8.2 The Basic Theory of Ellipsoidal Variable Stars

Succinctly put, ellipsoidal variable stars are binary (or multiple) star systems whose close proximity leads to significant physical and evolutionary influences on one or all of the stars forming the system. They are a subset of the more general class of stars known as close binary stars.

The ellipsoidal variables are characterized by low amplitude, nearly sinusoidal light variations with periods typically between 0.5 days and 3 days. The principal cause of this variation is distortion of the stellar surface or surfaces arising from tidal interactions between the stars and their companions. As a distinct class of stars only about two dozen have been classified as ellipsoidal but it is reasonable to expect that ellipsoidal variable stars are much more common than this would suggest$^{(4)}$.

8.2.1 The Roche Model

The analysis of tidal interaction between two rotating, fluid, self gravitating bodies is, in its most general form, a very complex one. A significant simplification of this problem is achieved if the assumption is made that the interacting bodies can be considered as point masses. The theory of stellar structure suggests that this assumption is warranted for main sequence and evolved stars. If it is further assumed that the bodies are orbiting each other in circular, tidally synchronized orbits the analysis reduces to the case considered by Edouard Roche, a French mathematician of the last century. In this form it is a special case of the three-body problem of classical mechanics.

By using the Roche model it is possible to construct the equipotential surfaces for a binary star system. These surfaces help to define not only the configurations of equilibrium for the stars but also to indicate important constraints on the geometry of the binary system.

To understand the Roche model consider Figure 8.1. In this diagram the two stars (masses m_1 and m_2) are separated by the distance A, which for convenience will be set equal to unity. If R represents the distance of the center of mass of the system from star 1 then the total potential (gravitational and centrifugal) for the co-rotating system can be written as

$$\Psi = \frac{Gm_1}{r_1} + \frac{Gm_2}{r_2} + \frac{1}{2}\,\omega^2\left\{\left[m_2/(m_1+m_2)-x\right]^2+y^2\right\} \qquad 8.1$$

where r_1 and r_2 are the separation of a test particle from m_1 and m_2, and x,y and z are the coordinates of the test particle and $R = m_2/(m_1+m_2)$.

If spherical polar coordinates are chosen as:

$$\begin{aligned} x &= r\cos\phi\sin\theta = r\lambda \\ y &= r\sin\phi\cos\theta = r\mu \\ z &= r\cos\theta = r\nu \end{aligned} \qquad 8.2$$

and $r_1 = r$, equation 8.1 becomes:

$$\Psi = \frac{Gm_1}{r_1} + \frac{Gm_2}{(1-2r\lambda+r^2)^{1/2}} + \frac{1}{2}\omega^2\left\{\left[m_2/(m_1+m_2) - x\right]^2 + y^2\right\} \qquad 8.3$$

When equation 8.3 is expanded and after some algebra the following expression results:

$$\Omega = \frac{1}{r} + q\left\{\frac{1}{(1-2r\lambda+r^2)^{1/2}} - r\lambda\right\} + \frac{1}{2}(1+q)r^2(1-\nu^2) \qquad 8.4$$

where $q = m_2/m_1$ = the mass ratio of the stars and

$$\Omega = \frac{\Psi}{Gm_1} - \frac{m_2^2}{2m_1^2(m_1+m_2)} \qquad 8.5$$

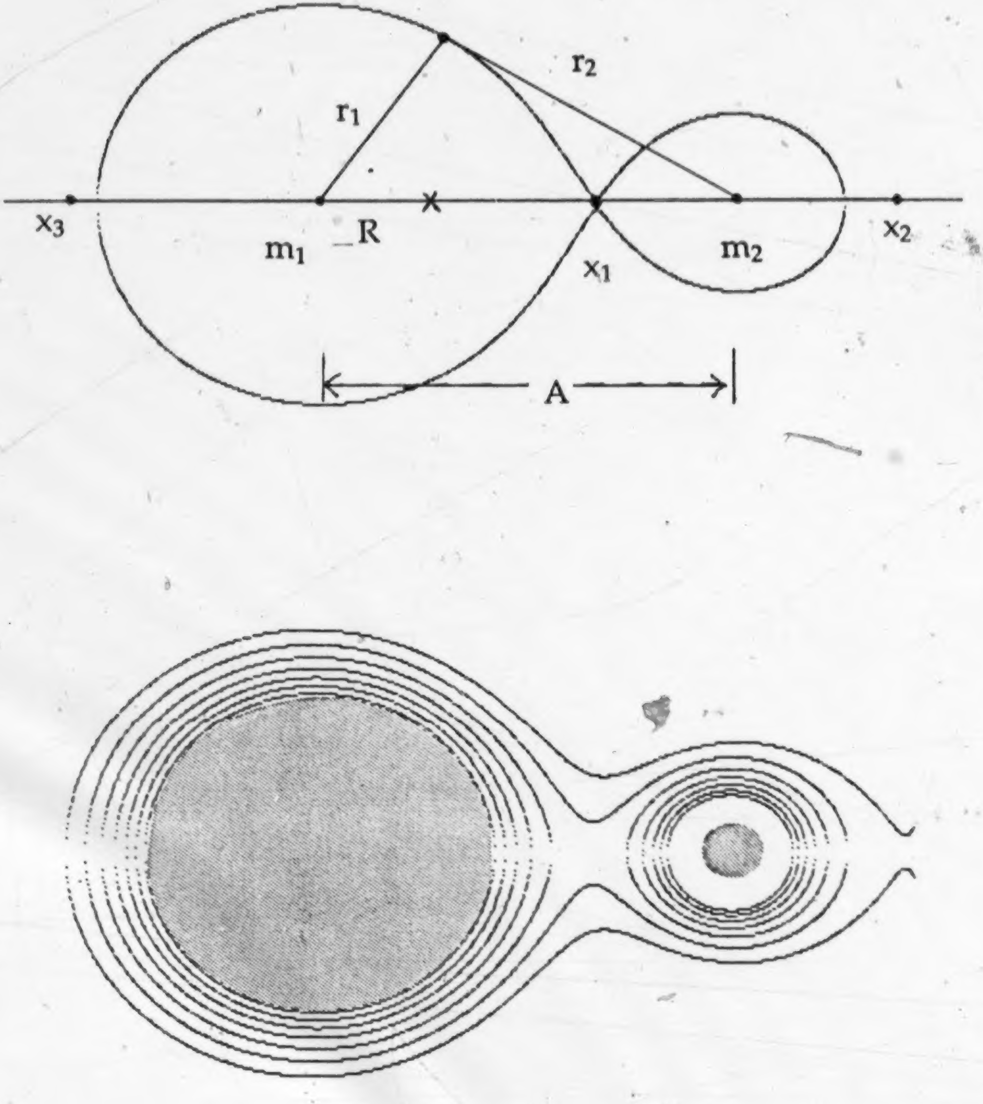

Figure 8.1. Top: A binary system with surrounding Roche equipotential surfaces. Points X_1, X_2, and X_3 locate the Lagrangian points for the system. In this example q $(m_2/m_1) = 0.19$. Bottom: Equipotentials for the 42 Persei system. The shaded ovals represent the dimensions of the stars as suggested by the model to be presented in this chapter.

is the dimensionless generalized Roche potential.

Equation 8.4 is usually solved numerically via a Newton-Raphson scheme(5) and defines the geometry of the binary star system. Setting Ω equal to a constant results in a surface of constant potential which is referred to as a **Roche Equipotential** surface. For large values of Ω the equipotential surfaces are two, nearly spherical surfaces surrounding each star of the system. In extreme cases, as Ω decreases, the equipotential surfaces become increasingly elongated into ellipsoid-like shapes. Since the surface of the star is defined by an equipotential surface, knowledge of the Roche equipotentials is essential in attempting to model accurately the shapes of tidally interacting stars. Figure 8.1 shows a binary system and the surrounding Roche equipotential surfaces.

As well as providing information on the possible shapes of the stars themselves, equation 8.4 places important constraints on the system as a whole. Of particular interest are the **Lagrangian points**, three of which are located along the line joining the centers of the two stars. These are designated X_1,X_2, and X_3 in figure 8.1 and correspond to those points for which $\Omega_x = 0$.

For example, the Lagrangian point, X_1 can be located by noting that r = x, y = z = 0, so that equation 8.4 becomes:

$$\Omega = \frac{1}{x} + q\left\{\frac{1}{1-x} - x\right\} + \frac{q+1}{2}x^2 \qquad 8.6$$

Setting $\Omega_x = 0$ and simplifying results in the following quintic equation:

$$(1+q)x^5-(2+3q)x^4+(1+3q)x^3-x^2+2x-1 = 0 \qquad 8.7a$$

Of particular importance is the fact that the roots of equation 8.7 depend only on the free parameter q - the mass ratio for the system. Physically, equation 8.7 locates the point of equilibrium between the two stars at which the net force on a test mass is zero. It is easy to show that this point represents an unstable equilibrium. If one star of the system swells (possibly through evolutionary changes) to reach the inner Lagrangian point, mass transfer can occur across this point. Mass exchange between members of close binary systems is believed to occur and profoundly influences the overall evolution of such systems. The location of the inner Lagrangian point X_1 defines the **Roche lobe** for the respective stars. These are "ellipsoid-like" volumes which represent the largest possible dimension of each individual star in the system beyond which evolution in isolation cannot occur.

As well as an inner point of equilibrium, there exist two other Lagrangian points along the line of centers for the system. Suitable modifications to equation 8.4 result in the following quintic equations for X_2 and X_3:

$$X_2:(1+q)x^5-(2+3q)x^4+(1+3q)x^3-(1+2q)x^2-2x+1 = 0 \qquad 8.7b$$

$$X_3:(1+q)x^5+(2+3q)x^4+(1+3q)x^3-x^2-2x-1 = 0 \qquad 8.7c$$

Points X_2 and X_3 represent the maximum size of the binary system. Matter reaching either of these points is rapidly lost from the system. Figure 8.2 shows the locations of the three axial Lagrangian points as a function of mass ratio. When constructing a model for a close contact binary system, careful attention must be paid to these points.

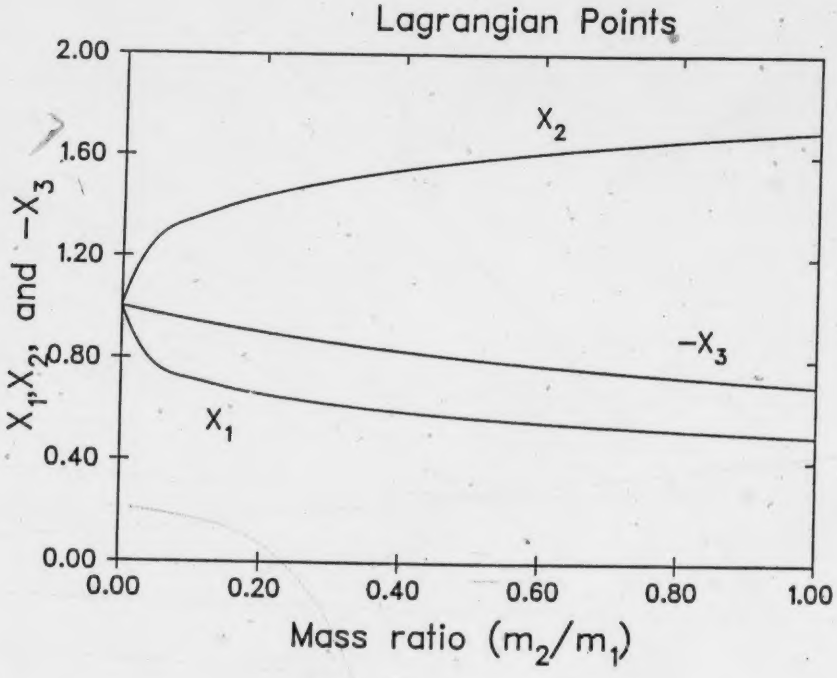

Figure 8.2 Graph showing the location of the 3 axial Lagrangian points as a function of mass ratio.

8.2.2 Brightness Variation Due to Changes in Projected Surface Area

As the Roche model suggests, one or both stars in an ellipsoidal binary system is distorted into a non-spherical configuration. As the star rotates, a continuously varying surface area is projected in the line of sight of a distant observer. The characteristc signature of this effect in the light curve of a variable star is a doubly periodic wave pattern. In the absence of eclipse, such distortion will be the dominant cause of brightness variation. For close, eclipsing binary systems significant departures from spherical stellar shapes results in a continuous variation of brightness outside of eclipse and is referred to as **ellipticity** in the light curve.

Although a precise determination of the shape of a close binary star requires a numerical solution to equation 8.4 , useful approximations can achieved by expanding this equation in terms of Legendre polynomials. Kopal(6) presents an extensive discussion of this procedure which will not be repeated here. In section 8.4 Kopal's procedure will be used to construct a simple model for 42 Persei.

Whether a numerical or analytic approach is used to determine the shape of the stellar surface, the problem facing the theorist is to integrate the brightness of the star or stars across that portion of the stellar surface visible to a distant observer. This introduces the additional complication of non-uniform brightness of the stellar surface due to limb and gravity darkening and reflection effects.

8.2.3 Limb Darkening, Gravity Darkening and Reflection

Even a casual inspection of the sun with a small telescope reveals a gradual diminution of brightness from the centre to edge of the solar disk. This occurs because, in our line of sight, light from the limb of the sun travels obliquely through the solar photosphere. Light emerging from the solar limb does so from higher and cooler layers of the photosphere. Measurement of the varying intensity of light from center to limb of the sun provides useful temperature versus depth information for the solar photosphere. Such an effect is called **limb darkening** and is an appreciable effect for most stars.

The brightness of the limb of a stellar disk may be typically less than half the brightness at the center of the stellar disk. The theory of stellar atmospheres suggests that the brightness distribution across the stellar surface can be approximated by:

$$I(\gamma) = I(0)\left(1 - \mu + \mu\cos(\gamma)\right) \qquad 8.8$$

where g is the angle (wrt the line of sight of a distant observer) between the center of the stellar disk and a point on the stellar disk. The limb darkening coefficient, μ, depends on the composition of the stellar photosphere as well as temperature and wavelength of the emergent light. The values of u used in this study were obtained from those published by Al-Naimiy(7).

In addition to limb darkening, gravity darkening can also play a significant role in the brightness distribution across the stellar surface. According to von Zeipel's theorem, the flux emerging from the stellar surface is proportional to the intensity of the gravitational field at that point. In the case of a rotationally or tidally distorted star, the surface gravity and hence brightness is not constant across the stellar disk. Usually the polar regions are brighter than the equatorial regions. As well, in the case of a tidally distorted star, gravity darkening is greatest at the point on the stellar surface facing the other star. This can be expressed via the formula

$$\frac{F_{local}}{F_{pole}} = (\nabla\Omega)^{g} \qquad 8.9$$

where Ω is the gravitational potential (normalized wrt the pole) and F_{local} and F_{pole} are the fluxes at some point on the stellar surface and at the pole, respectively. The coefficient 'g' is the gravity darkening coefficient and ranges from a value of 1 (for a purely radiative stellar envelope) to values on the order of 0.25 for stars in which convection is an important energy transport mechanism(8).

A final effect to be considered is the heating of one star due to the proximity of the other. The subsequent re-radiation of energy due to this increased heating is termed reflection. The reflection effect is poorly understood and difficult to model. In actual practice it often appears as an adjustable parameter used to improve the fit of a synthetic light curve to observation. In extreme cases reflection leads to non-symmetric light curves, elevating one of the principal maxima in relation to the other.

When the limb darkening, gravity darkening and reflection effects are combined with the changing surface area presented by one or both of the members of a close binary system it becomes possible to generate synthetic light curves allowing a comparison between theory and observation. When additional information is provided concerning the orbital period and orientation of the star system it is possible to construct a model for that system.

8.3 The Data

The UBV photometric data reported here were obtained with the two channel photometer on the 0.5-m Cassegrain reflector at the Devon Astronomical Observatory. (The photometer was operated in a single channel mode due to the lack of a suitable comparison star within the limited field of the photometer.) An uncooled EMI 9840 tube and Ortec photon counting electronics were used for all observations reported here.

8.3.1 Data Reduction Methods Used in This Study

Standard techniques of classical differential photometry have been applied in the study of 42 Persei and the other stars discussed in this thesis. An excellent discussion of the theory behind these techniques is provided by Henden and Kaitchuck(9). What follows will be a very brief discussion of differential photometry.

The principal problem facing the photometrist is to distinguish between intrinsic variations in the brightness of the star and those changes due to variable atmospheric and instrumental effects. Of these effects, atmospheric extinction or the attenuation of starlight as it passes through the atmosphere, is the most significant. In carrying out a first order extinction correction the dominant variable to consider is the amount of atmosphere or **air mass** through which the starlight passes. This can be expressed in the following form:

$$\begin{aligned} v_0 &= v - k'_v X \\ b_0 &= b - k'_b X \\ u_0 &= u - k'_u X \end{aligned} \qquad 8.10$$

where v,b,u are the instrumental magnitudes in the v,b, and u band pass filters, k'_v, k'_b,and k'_u are the first order extinction coefficients and v_o,b_o, and u_o are the corrected instrumental magnitudes. The air mass, X is, to a high degree of accuracy given by the expression

$$X = \sec Z \qquad 8.11$$

where Z is the zenith distance or spherical angle between the star and the zenith point.

If a set of measures for v, b and u are obtained, the slope of a graph relating one of these instrumental magnitudes to air mass will indicate the corresponding first order extinction coefficient for that filter. The vertical intercept of the graph indicates the appropriate corrected instrumental magnitude (ie. its instrumental magnitude measured from the top of the atmosphere). Figure 8.3 provides an example of this showing the b filter first order extinction graph for HR1164 on the night of February 17, 1989. The goodness of fit suggests that the sky was very steady on this night and that equation 8.10 provides a reasonable approximation of the effects of atmospheric extinction. The first order correction in the b filter was 0.285 ± 0.004 (mag/air mass) and $b_0 = 5.720 \pm 0.003$ mag

The reliability of equation 8.10 rests on the assumption that the extinction coefficients remain constant both in time and with respect to airmass. Neither of these assumptions can, in general, be held with confidence and the usual way to minimize these uncertainties is to compare the v,b and u magnitudes of two similar (if possible) stars situated close to each other. In the case of 42 Persei, the star HR 1164 was chosen as a comparison star. HR 1164 is a G0 star and has proven to be constant in brightness over the several seasons that it has been observed in this study. As an additional comparison - to monitor the reliability of HR 1164 - the UBV cluster standard HR 1172 has also been observed.

Throughout the night observations are taken in succession between a program star (42 Persei), a comparison star (HR 1164) and periodically a check star (HR 1172). In the case of 42 Persei the observing sequence usually consisted of several sequences of 5 u,b and v filter integrations of 20 second duration each bracketed by a similar set of u,b v observations of HR 1164. To minimize the effects of any time variation of extinction coefficients the time between observations of the comparison star should be kept as small as is practical.

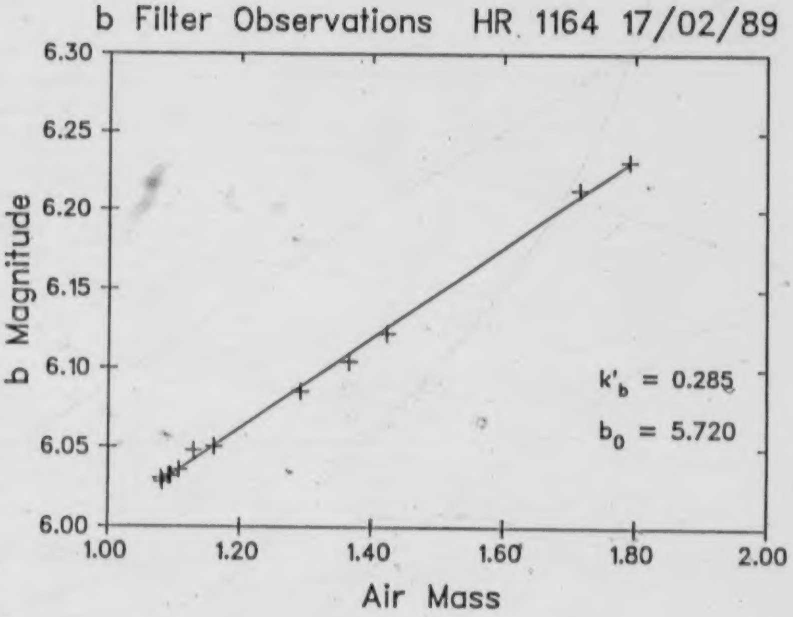

Figure 8.3 First order extinction graph for instrumental b magnitude of HR 1164 on the night of February 17, 1989.

Now, instead of using equation 8.10, the differential expressions:

$$\begin{aligned} \Delta v_0 &= \Delta v - k'_v \Delta X \\ \Delta b_0 &= \Delta b - k'_b \Delta X \\ \Delta u_0 &= \Delta u - k'_u \Delta X \end{aligned} \qquad 8.12$$

are employed, where:

$$\begin{aligned} \Delta v_0 &= (v_0^{pgm} - v_0^{check});\ \text{etc.} \\ \Delta X &= (X_{pgm} - X_{check}) \end{aligned} \qquad 8.13$$

If ΔX is small, variations in the extinction corrections are minimal - providing there are no rapid changes in sky condition (ie. due to high cirrus cloud or aurora).

Another atmospheric effect that must be removed from the measurements is the brightness of the sky itself. This is in fact the first correction made to the data and consists of a simple subtraction of the number of counts per second from an "empty" region of the sky close to the program star and the counts received each second from the program or check star. Throughout the evening measurements of sky brightness are made, usually bracketing the program-comparison star sequences. Figure 8.4 shows a typical plot of sky brightness measured in the b filter for the evening of February 11, 1989.

A final complication that arises is the need to estimate the sky and comparison star brightness at the time of observation of the program star. For the data presented here this has been accomplished by use of a cubic spline interpolating routine.

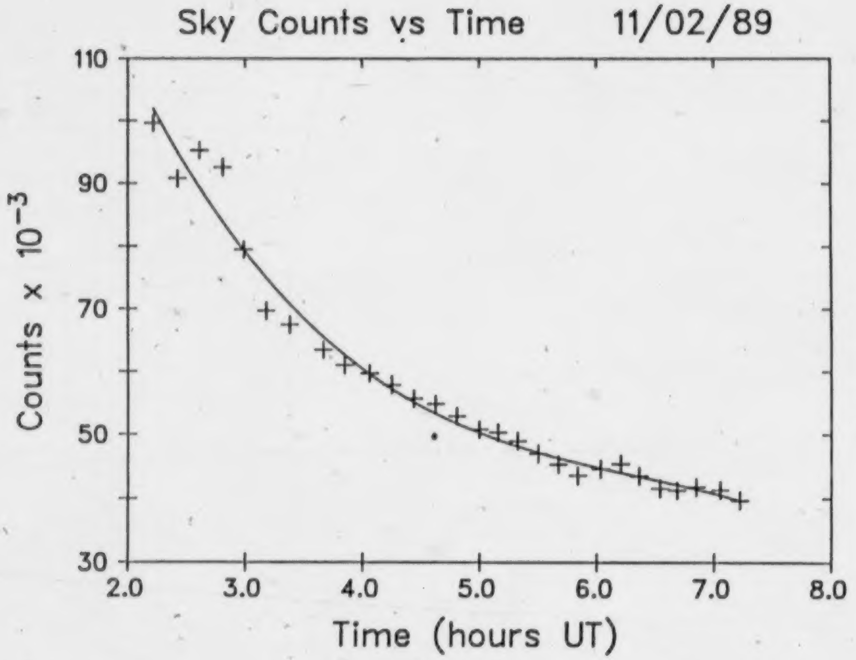

Figure 8.4 Plot of sky brightness measured in the b filter on the night of February 11, 1989.

In addition to atmospheric effects, the equipment itself can introduce errors that, if unrecognized could seriously compromise the quality of the data collected. The most serious equipment error is usually the **dead time loss** in a photometer/electronics system. This occurs because of the finite interval of time required for a photometer system to respond to the arrival of a photon.

For very bright stars the number of photons arriving each second is enormous and can "swamp" the system. This causes some counts to be "missed". Fortunately, the electronics used in the observations reported here have proven to be fast enough so that dead time losses are negligible for the stars described in this study.

8.3.2 Transformation to the UBV Standard System

In order to permit comparison of the observations made at the Devon observatory with data from other observatories it is necessary to convert all u,b,v magnitude measures to the standard U,B,V system. This is accomplished by comparing the u,b,v magnitude measures of selected standard stars with their published values. Each band pass filter and photomultiplier has its own particular sensitivity. By carefully observing a small number of suitably chosen standard stars one can derive a set of transformation coefficients that make the conversion from local magnitude measures to the standard system a relatively easy procedure. Table 8.1 lists data obtained for 5 Pleiades standard stars on the night of February 17, 1989. This was a night of excellent photometric quality and provided the data used to determine the UBV transformation coefficients.

The equations of transformation used are:

$$V = v_0 + \varepsilon(B\text{-}V) + \zeta_v \qquad 8.14a$$

$$(B\text{-}V) = \mu(b\text{-}v)_0 + \zeta_{bv} \qquad 8.14b$$

$$(U\text{-}B) = \Psi(u\text{-}b)_0 + \zeta_{ub} \qquad 8.14c$$

where ε , μ and ψ are the transformation coefficients in the V, B and U filters respectively. The ζ terms are the zero point corrections in each of the three filters. The subscripted terms in v, (b-v) and (u-b) refer to reduced instrumental magnitudes. Figures 8.5-8.7 show the graphs used to determine the V,B and U transformation coefficients and Table 8.2 lists the data and regression analysis for each coefficient. The adopted values for UBV tranformations of the Devon data throughout the observing period under discussion are: $\varepsilon = -0.166 \pm 0.007$ (s.e.) , $\mu = 1.133 \pm 0.007$ (s.e.), and $\psi = 1.059 \pm 0.005$ (s.e.).

When the transformations are used differentially, equations 8.13 of section 8.3.1 become:

$$\Delta V = \Delta v + \varepsilon(B-V)_0 \qquad 8.15a$$
$$\Delta(B-V) = \mu\Delta(b-v)_0 \qquad 8.15b$$
$$\Delta(U-B) = \Psi\Delta(u-b)_0 \qquad 8.15c$$

UBV Transformation Coefficients
Feb 17/89

Based on Pleiades standard stars:

HR 1172
D
F
G
H

(Henden & Kaitchuck notation, page 299)

First order extinction coefficients (determined from HR 1164)

k'(v) = 0.158
k'(b) = 0.285
k'(u) = 0.583
k'(bv) = 0.125
k'(ub) = 0.298

Star	V	B-V	U-B	v	b	u	u-b	X
HR 1172	5.450	-0.070	-0.320	5.713	4.762	5.918	1.156	1.375
		-0.070		5.804	4.927	6.246	1.319	1.935
D	6.460	1.700	2.070	6.977	7.632	11.025	3.393	1.263
		1.700		7.048	7.737	11.251	3.514	1.695
F	6.950	0.120	0.090	7.218	6.427	7.977	1.550	1.298
		0.120		7.302	6.585	8.270	1.685	1.805
G	7.420	0.130	0.120	7.692	6.902	8.478	1.576	1.279
		0.130		7.765	7.041	8.742	1.701	1.738
H	7.720	1.230	1.120	8.208	8.449	10.971	2.522	1.333
		1.230		8.307	8.597	11.284	2.687	1.887

Table 8.1 U,B and V filter transformation coefficient data derived from measures of five Pleiades standard stars on February 17, 1989.

Regression Analysis for UBV Transformation Coefficients

ε

(B-V)	V - v + kX
-0.0700	-0.04827
-0.0700	-0.04575
0.1200	-0.06292
0.1200	-0.06681
0.1300	-0.06992
0.1300	-0.07040
1.2300	-0.27739
1.2300	-0.28885
1.7000	-0.31745
1.7000	-0.32019

Regression Output:	
Constant	-0.05343
Std Err of Y Est	0.01655
R Squared	0.98440
No. of Observations	10.00000
Degrees of Freedom	8.00000
X Coefficient(s)	-0.16617
Std Err of Coef.	0.00740

μ

(b-v)'-kX	(B-V)
-1.0967	-0.0700
-1.0849	-0.0700
-0.9327	0.1300
-0.9296	0.1200
-0.9167	0.1300
-0.9160	0.1200
0.0431	1.2300
0.0679	1.2300
0.4537	1.7000
0.4805	1.7000

Regression Output:	
Constant	1.16928
Std Err of Y Est	0.01338
R Squared	0.99971
No. of Observations	10.00000
Degrees of Freedom	8.00000
X Coefficient(s)	1.13276
Std Err of Coef.	0.00677

k"(bv) = 0.02

ψ

(u-b)- kX	(U-B)
0.7423	-0.3200
0.7462	-0.3200
1.1471	0.0900
1.1632	0.0900
1.1830	0.1200
1.1948	0.12000
2.1247	1.1200
3.0088	2.0700
3.0166	2.0700

Regression Output:	
Constant	-1.12575
Std Err of Y Est	0.01342
R Squared	0.99981
No. of Observations	10.00000
Degrees of Freedom	8.00000
X Coefficient(s)	1.05870
Std Err of Coef.	0.00518

Table 8.2 Regression analysis for the UBV transformation coefficients. Analysis based on data given in Table 8.1.

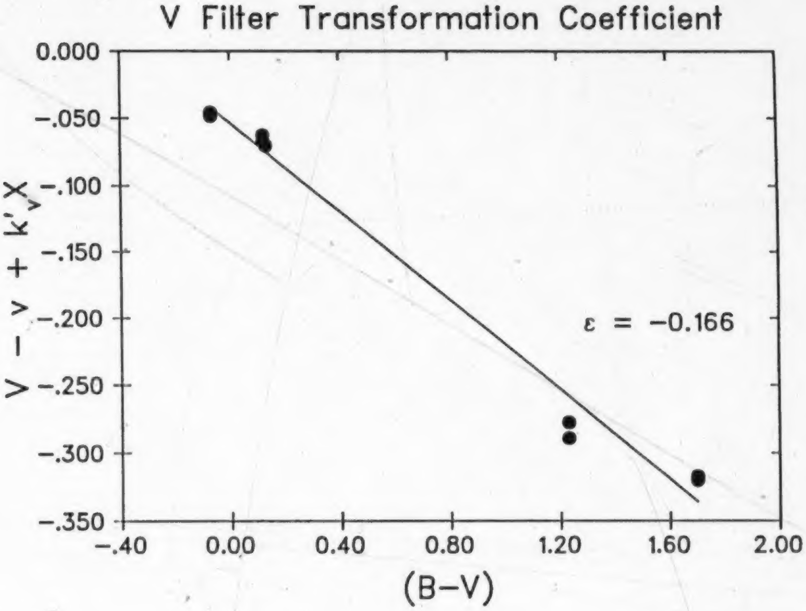

Figure 8.5 Plot of ($V - v_0$) versus (B - V) for selected Pleiades standard stars. V filter transformation coefficient is the slope of this line, ε = -0.166.

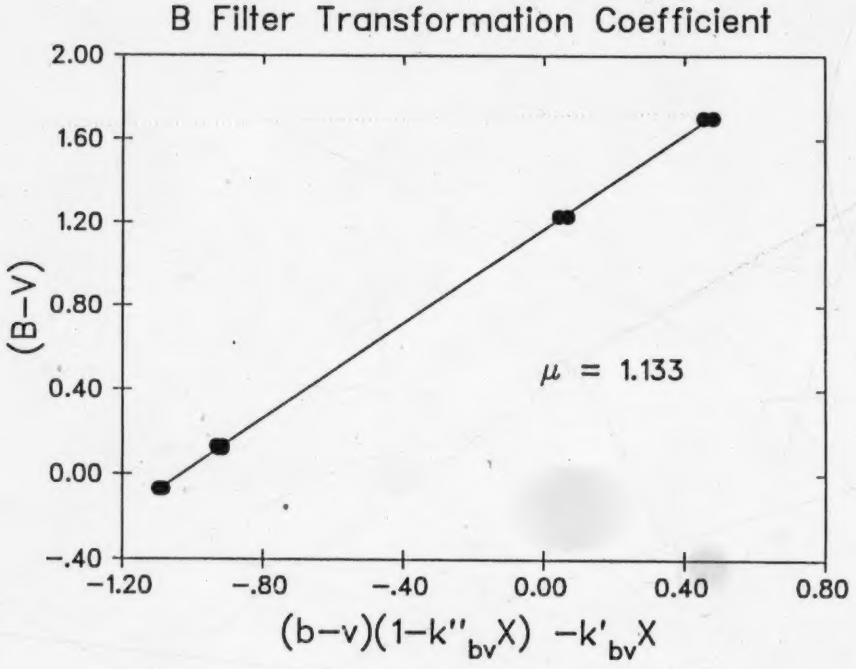

Figure 8.6 Plot of (B -V) versus (b - v)0 for selected Pleiades standard stars. B filter transformation coefficient is the slope of this line, μ = 1.133.

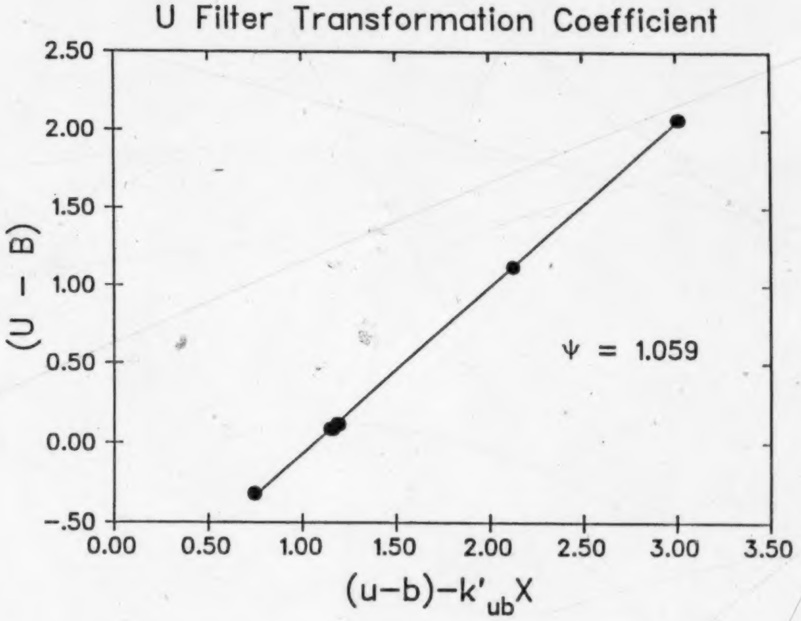

Figure 8.7 Plot of (U - B) versus (u - b)0 for selected Pleiades standard stars. U filter transformation coefficient is the slope of this line, ψ = 1.059.

Inserting the appropriate values for ε, μ, and ψ and isolating ΔV, ΔB, and ΔU yields:

$$\Delta V = 1.188\Delta v_0 - 0.188\Delta b_0 \tag{8.16a}$$

$$\Delta B = 0.055\Delta v_0 + 0.945\Delta b_0 \tag{8.16b}$$

$$\Delta U = 0.055\Delta v_0 - 0.120\Delta b_0 + 1.059\Delta u_0 \tag{8.16c}$$

as the equations of transformation of the (42 Persei - HR 1164) system.

8.3.3 The Photometric Variation

Table 8.3 gives the differential magnitudes for (42 Persei- HR 1164) averaged in phase bins of width 0.01. The total number of observations (prior to averaging) in U, B and V are 228, 259, and 383 respectively.

Figures 8.8 - 8.11 shows the data phased with a period of 1.7653511 days and with respect to the epoch date of T(JD) = 2437638.8047. It is readily apparent from these figures that the U,B ,and V light curves possess the doubly-periodic form characteristic of ellipsoidal variability.

A fourth order Fourier series of the form

$$\Delta m = A_0 + \sum_{i=1}^{i=4}\left(A_i\cos(\theta i) + B_i\sin(\theta i)\right) \tag{8.17}$$

was used to fit the data in each of the three colors where θ is the orbital phase. A weighted multiple linear regression analysis (MINITAB) was used to perform a Fourier least squares fit up to fourth order terms.

As expected, the cos(2θ) term was dominant. Table 8.4 gives the coefficients for the sine and cosine terms. The average standard deviations for the coefficients are 0.0013, 0.0007, 0.0007 magnitude for U, B, and V respectively. The Fourier series are plotted with the observations in Figures 8.8 - 8.11. Figures 8.12 - 8.14 show the difference between the U,B and V filter data and their respective Fourier fits. These 'observed - predicted', (O-C), plots suggest that if an eclipse is present in the system it must be very small (less than 1% in depth).

UBV Data for (42 Persei - HR 1164) in 0.01 phase bins

Phase	U Mag	B Mag	V Mag
0.0000			
0.0100			
0.0200			
0.0300	1.3202	1.5149	1.1111
0.0400	1.3154	1.5083	1.1118
0.0500	1.3225	1.5125	1.1140
0.0600	1.3213	1.5078	1.1103
0.0700	1.3240	1.5110	1.1117
0.0800	1.3202	1.5049	1.1080
0.0900	1.3218	1.5102	1.1082
0.1000	1.3178	1.5046	1.1057
0.1100	1.3149	1.5023	1.0951
0.1200	1.3155	1.5013	1.0972
0.1300	1.3120	1.4984	1.0926
0.1400	1.2938	1.4805	1.0870
0.1500	1.2930	1.4827	1.0826
0.1600			
0.1700	1.3032	1.4778	1.0802
0.1800	1.2941	1.4741	1.0733
0.1900	1.2884	1.4712	1.0717
0.2000	1.2864	1.4731	1.0751
0.2100	1.2880	1.4605	1.0711
0.2200			
0.2300			
0.2400			
0.2500	1.2511	1.4560	1.0547
0.2600	1.2669	1.4551	1.0592
0.2700	1.2676	1.4523	1.0564
0.2800			
0.2900	1.2626	1.4507	1.0538
0.3000	1.2658	1.4555	1.0588
0.3100	1.2627	1.4512	1.0586
0.3200	1.2771	1.4694	1.0626
0.3300	1.2554	1.4510	1.0637
0.3400			
0.3500			
0.3600	1.2933	1.4778	1.0766
0.3700	1.2957	1.4802	1.0819
0.3800	1.2943	1.4844	1.0879
0.3900	1.2939	1.4881	1.0882
0.4000	1.3038	1.4875	1.0894
0.4100	1.3181	1.4978	1.0986
0.4200	1.3083	1.4972	1.0995
0.4300	1.3130	1.4981	1.1031
0.4400	1.3155	1.5016	1.0943
0.4500	1.3167	1.5064	1.0948
0.4600	1.3185	1.5082	1.0975
0.4700	1.3191	1.5069	1.0991
0.4800	1.3247	1.5105	1.1050
0.4900	1.3126	1.5130	1.1067
0.5000		1.5136	1.1084
0.5100		1.5139	1.1039
0.5200		1.5141	1.1167
0.5300		1.5114	1.1156
0.5400		1.5097	1.1096
0.5500		1.5088	1.1111
0.5600		1.5086	1.1065
0.5700			
0.5800			
0.5900			
0.6000			
0.6100		1.4836	1.0907
0.6200		1.4758	1.0922
0.6300		1.4738	1.0863
0.6400	1.3074	1.4661	1.0949
0.6500			
0.6700	1.2913	1.4745	1.0770
0.6800	1.2850	1.4631	1.0805
0.6900		1.4734	1.0881
0.7000	1.2846	1.4731	1.0802
0.7100	1.2758	1.4788	1.0794
0.7200		1.4824	1.0845
0.7300	1.2928	1.4776	1.0796
0.7400			
0.7500			
0.7600			
0.7700			
0.7800			
0.7900	1.2833	1.4754	1.0750
0.8000	1.2764	1.4686	1.0783
0.8100	1.2863	1.4694	1.0744
0.8200	1.2888	1.4731	1.0749
0.8300	1.2973	1.4804	1.0794
0.8400	1.2907	1.4774	1.0784
0.8500	1.2976	1.4812	1.0806
0.8600	1.2999	1.4843	1.0813
0.8700	1.2981	1.4819	1.0827
0.8800	1.2967	1.4823	1.0833
0.8900	1.3034	1.4847	1.0859
0.9000	1.3017	1.4893	1.0918
0.9100	1.2998	1.4877	1.0895
0.9200			
0.9300	1.3059	1.4889	1.0920
0.9400	1.3169	1.4981	1.1032
0.9500			
0.9600			
0.9700		1.5031	1.1017
0.9800		1.5044	1.1051
0.9900			

Table 8.3 UBV data for (42 Persei - HR 1164) phased in intervals of width 0.01.

Fourier Coefficients

	A_0	A_1	A_2	A_3	A_4	B_1	B_2	B_3	B_4
V	1.0881	0.0014	0.0206	-0.0004	-0.0005	-0.0040	0.0060	0.0039	0.0006
B	1.4864	0.0017	0.0233	-0.0044	-0.0014	-0.0027	0.0044	0.0060	0.0000
U	1.2992	0.0024	0.0222	-0.0044	-0.0023	-0.0033	0.0058	0.0048	-0.0019

Table 8.4 Fourier coefficients from a fourth order fit for the photometric variation of 42 Persei.

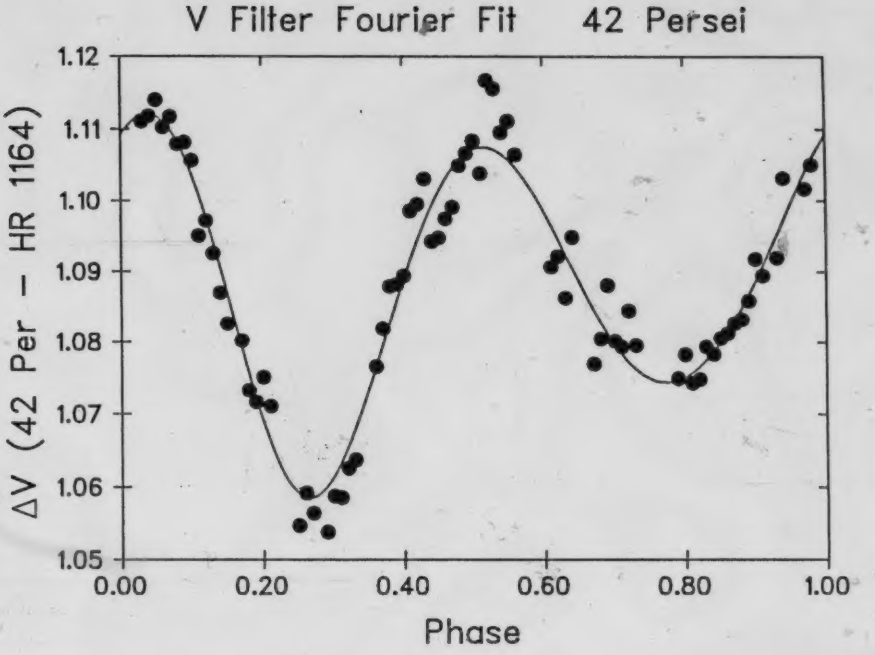

Figure 8.8 V filter observations of (42 Persei - HR 1164) phased in bins of width 0.01. Phasing is wrt a period of 1.7653511 days and from epoch date T_0 = 2437638.8047. The solid line represents a least squares fourth order Fourier fit through the data.

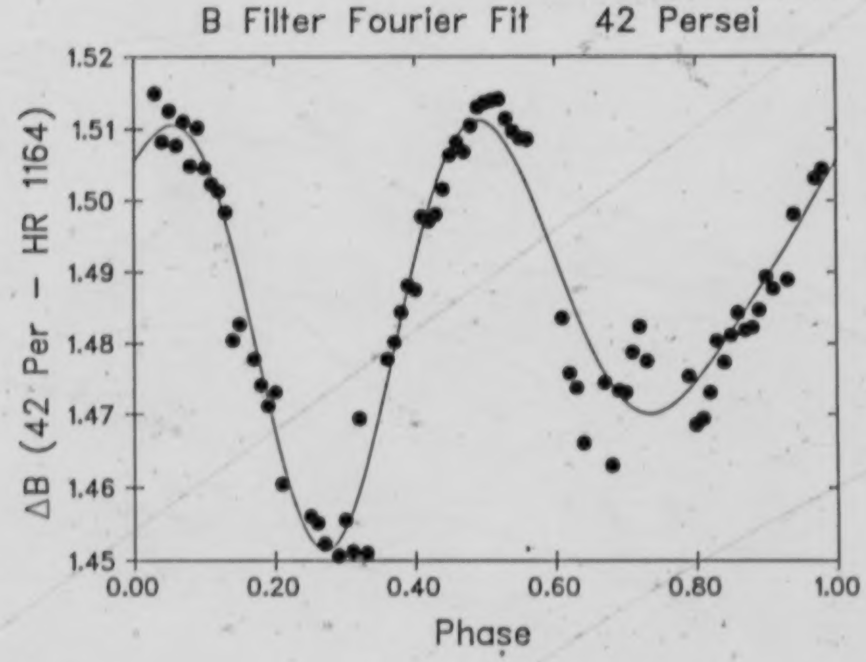

Figure 8.9 B filter observations of (42 Persei - HR 1164) phased in bins of width 0.01. Phasing is wrt a period of 1.7653511 days and from epoch date $T_0 = 2437638.8047$. The solid line represents a least squares fourth order Fourier fit through the data.

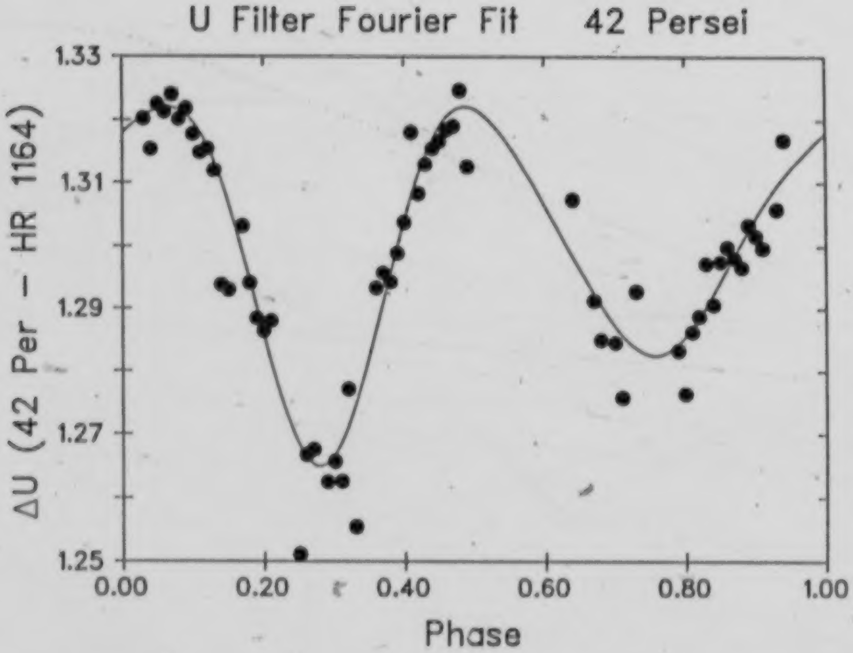

Figure 8.10 U filter observations of (42 Persei - HR 1164) phased in bins of width 0.01. Phasing is wrt a period of 1.7653511 days and from epoch date T_0 = 2437638.8047. The solid line represents a least squares fourth order Fourier fit through the data.

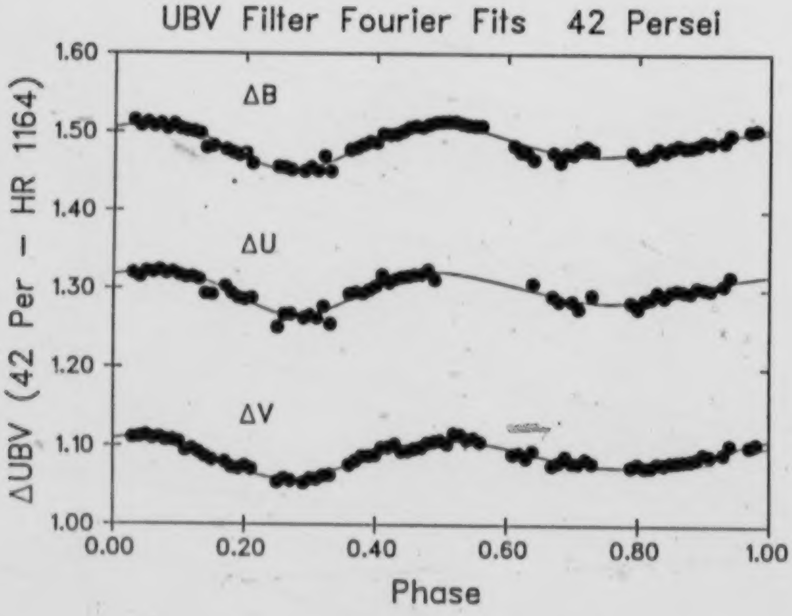

Figure 8.11 U,B, and V filter observations and Fourier fits for (42 Persei - HR 1164).

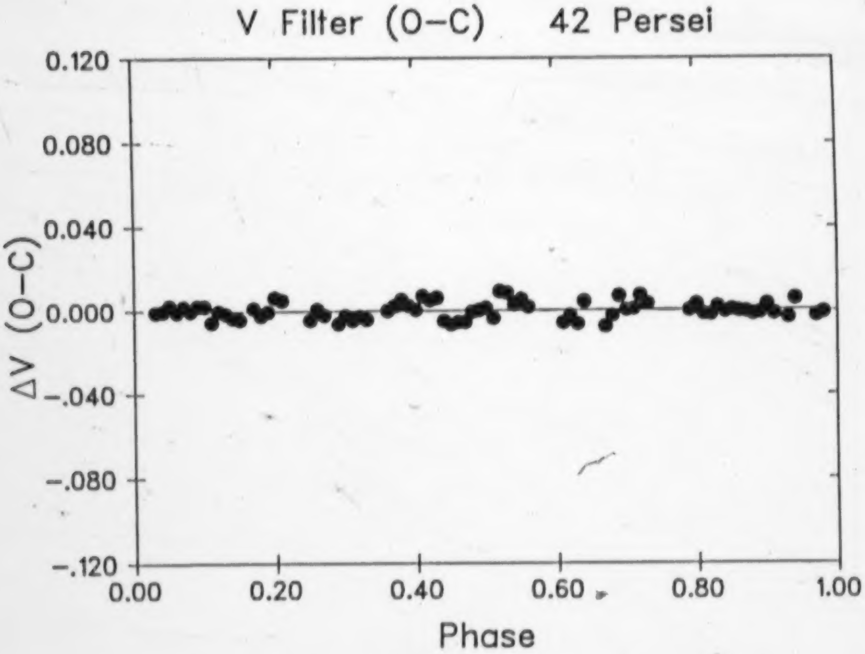

Figure 8.12 V filter (O - C) for (42 Persei - HR 1164).

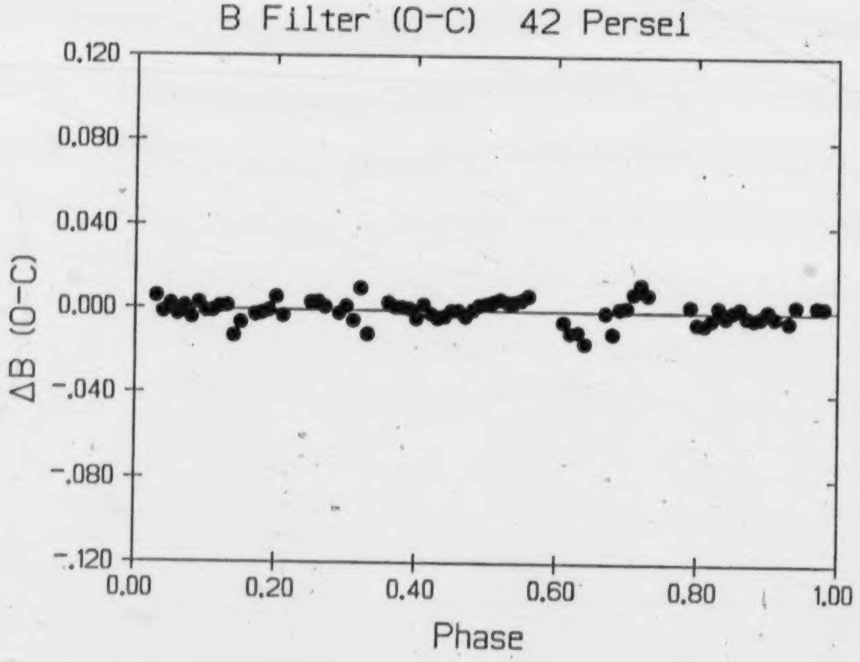

Figure 8.13 B filter (O - C) for (42 Persei - HR 1164).

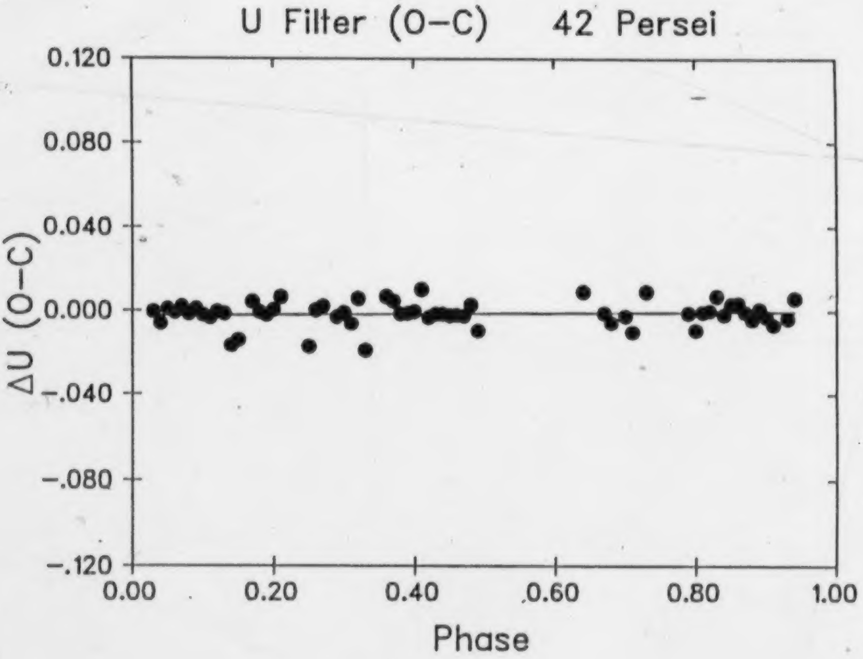

Figure 8.14 U filter (O - C) for (42 Persei - HR 1164).

8.3.4 Radial Velocities

The latest radial velocities available to Morbey and Brosterhus were obtained more than two decades ago. On five nights in February, 1988, Hube obtained an additional 9 spectra at dispersion of 1.5 nmmm^{-1} using a Reticon detector and the Cassegrain spectrograph on the 1.88 m reflector at the Dominion Astrophysical Observatory (DAO), Victoria, British Columbia.

The spectra covered the wavelength region from approximately 405 nm to 450 nm, and were measured using cross-correlation techniques and the program VCROSS(10). The hydrogen lines were not included in the cross-correlation.

Heliocentric corrections were applied to the apparent radial velocities. Observations of the standard velocity star HD 136202 resulted in a small correction being applied to reduce the radial velocities to the I.A.U. velocity system. The new heliocentric radial velocities of 42 Persei are presented in Table 8.5. The complete radial velocity data set is shown in Figure 8.15 with the new observations denoted by triangles.

On average, the radial velocities obtained in 1988 were displaced to slightly later phases as compared with the earlier velocities when the orbital elements found by Morbey and Brosterhus were used. This implied the need to adopt a slightly longer period. While the period of 1.7653511 days does satisfy all the available radial velocities and the photometry, one cannot exclude the possibility that period changes have occurred between the earliest and the latest observations. If such changes were known and allowed for, the scatter in the radial velocity data might be reduced.

8.3.5 Orbital Elements

Using the Lehmann-Filhés equation of condition, Hube has obtained a new spectroscopic orbit solution by combining the 9 new radial velocities with 35 of the older published velocities which we (and Morbey and Brosterhus) considered reliable.

The elements from this solution are presented in Table 8.6 with their formal standard errors.

8.4 The Simple Model

As a zeroth order model for the 42 Persei system, it has been assumed that the observed photometric variability can be attributed solely to ellipsoidal distortion in the primary star. The lack of any obvious asymmetry in the two maxima of the light curves suggests that reflection is not significant and leads one to conjecture that the secondary star of the system is much smaller than the primary. Using a discussion due to Morris(11) based on the earlier work of Kopal(12) the amplitude of the cos(2θ) term can be related to various physical parameters describing the system through the following expression:

$$\frac{qR_1\sin^2 i}{a^3} = \frac{3.07(\Delta m_1)(3-u_1)}{(t_1+1)(15+u_1)} \qquad 8.18$$

where q is the mass ratio, R_1 is the radius of the primary and a is the semimajor axis of the relative radius (both in solar units). Δm_1 is the amplitude of the light variation (twice the amplitude of the cos (2θ) term), u_1 and t_1 are the limb and gravity darkening coefficients of the primary star.

Consistent with the assumptions of the Roche model, it is assumed that the stars are tidally locked with rotational motion synchronized with the orbital motion relative to the center of mass of the system. Since the eccentricity of the orbit is very nearly circular (0.056 ± 0.041) and the period is very short (1.765351^d) this seems to be a reasonable choice. The validity of this assumption will be discussed in the conclusions of this chapter.

When the assumption of tidal synchronization is made it becomes possible to infer the radius of the primary star by comparing the circular orbital velocity of the primary with its rotational velocity via the expression:

Radial Velocities for 42 Persei

Julian Date	Phase	V (km/s)	Julian Date	Phase	V (km/s)
19291.9440	0.7546	-19.50	25906.9880	0.5997	-34.80
19315.9680	0.1459	12.60	37573.6200	0.9245	26.00
19342.8930	0.8940	8.20	37586.5200	0.6172	-45.00
19401.7790	0.5375	-39.70	37587.5800	0.0167	19.00
19701.8330	0.5690	-35.30	37607.4800	0.7442	-11.00
19710.8100	0.4839	-43.70	37608.5400	0.1437	14.00
19716.6940	0.1509	11.60	37608.5600	0.1324	20.00
19726.6670	0.5016	-54.80	37640.4000	0.9037	27.00
19735.6490	0.4136	-46.50	37651.4200	0.1461	-9.00
19737.6170	0.2988	-14.30	47214.6750*	0.3432	-25.90
19749.5890	0.5172	-47.90	47214.6848	0.3488	-27.10
19767.6490	0.2869	-29.80	47215.6187	0.8778	10.50
19789.5880	0.8594	9.40	47216.6227	0.4465	-44.40
19806.5280	0.2635	-13.10	47216.7175	0.5002	-41.70
20482.7160	0.2304	-13.80	47218.6222	0.5792	-42.50
20484.7120	0.0997	6.30	47218.7246	0.6372	-31.70
20502.6760	0.9239	19.70	47219.6148	0.1414	15.80
20505.6420	0.2437	-11.40	47219.7322	0.2079	3.60
20513.6150	0.7274	-9.70			
20523.6380	0.0497	21.30			
20526.5750	0.3860	-34.80			
20546.5610	0.0648	15.60			
20370.8700	0.5866	-44.00			
20407.8020	0.6661	-28.00			
20408.7440	0.1325	19.00			
20464.6970	0.4374	-50.00			

* observations on and after this date by Hube, Feb/88.

Table 8.5 Radial velocity data for 42 Persei.

Spectroscopic Orbital Elements of 42 Persei

Element	Value	std. error
Period, P (days)	1.7653511	± 0.0000020
Systemic velocity, Γ (km s^{-1})	-11.73	± 0.03 (se)
Semi amplitude, K (km s^{-1})	34.34	± 1.37
Eccentricity, e	0.056	± 0.041
Long. of perihelion, Ω (°)	256.8	± 46.1
Epoch of mean long., T_0	2437640.064	± 0.229
Projected semimajor axis, a_1 sini (10^6 km)	0.832	± 0.033
Mass function, F(m)(M_0)	0.0074	± 0.0009

Table 8.6 Spectroscopic solution for 42 Persei.

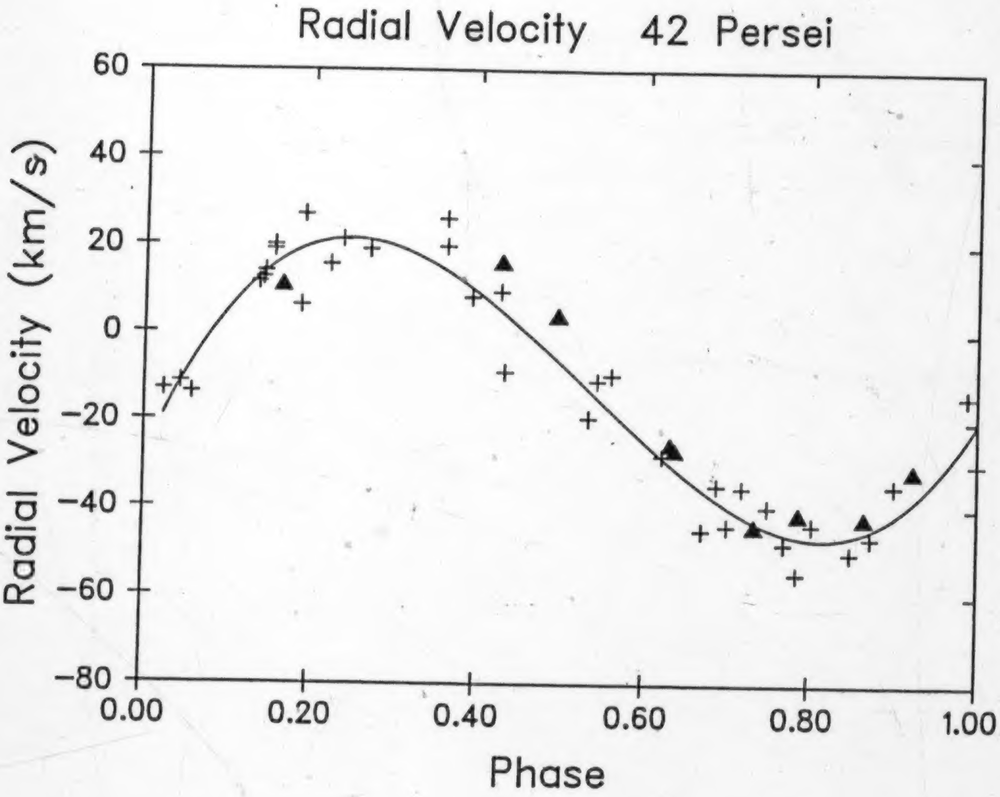

Figure 8.15 Radial velocities for 42 Persei. Triangles denote new observations by Hube, February 1988.

$$v\sin\, i = \frac{50.6(R_1)\sin\, i}{P} \qquad 8.19$$

where P is the period measured in days and radii are measured in solar units. The line profile fitting routines in VLINE(13) were applied to the Mg II (448.1 nm) line to obtain a projected rotational velocity (vsini) of 90.6 ± 0.8 km/s for the primary star.

This is combined with Kepler's third law in the form

$$a = 4.207(P^{2/3})(M_1+M_2)^{1/3} \qquad 8.20$$

as well as the expression for the mass function

$$\mathcal{F}(M) = \frac{M_2^3 \sin^3 i}{(M_1+M_2)^2} \qquad 8.21$$

An iterative procedure was used to solve these expressions for both B and V filter data. This resulted in a family of solutions which is given in Table 8.7 and shown graphically in Figure 8.16.

Possible solutions for various
Mass, mass ratio, inclination and mass function

M_1	q	i	M_2	F
1.900	0.190	72.0	0.361	0.0079
1.900	0.184	68.0	0.350	0.0067
1.900	0.187	70.5	0.355	0.0074
2.000	0.190	64.5	0.380	0.0071
2.000	0.191	65.3	0.382	0.0074
2.000	0.187	63.0	0.374	0.0066
2.100	0.195	62.0	0.409	0.0075
2.200	0.200	59.0	0.440	0.0077
2.200	0.198	58.4	0.436	0.0074
2.200	0.203	60.0	0.447	0.0083

"Best" solution:Parameters used:

			limb darkening	gravity darkening
M_1 =	2.0 (A3V)	U	0.41	1.02
M_2 =	0.38	B	0.54	0.87
q =	0.191	V	0.45	0.73
i =	65.3			
R =	3.48			
a =	8.207			

Table 8.7 Family of solutions to equations 8.18 - 8.21 suggesting possible model parameters for 42 Persei.

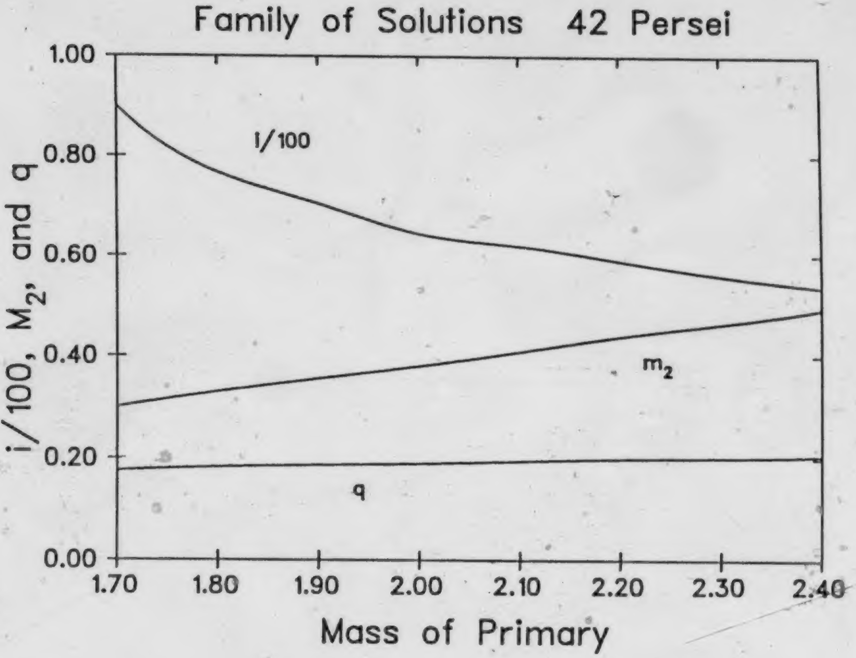

Figure 8.16 Family of possible solutions for 42 Persei based upon simple analytic model of Kopal. "Best" solution corresponds to $M_1 = 2.0\ M_\odot$, $M_2 = 0.38\ M_\odot$, $q = 0.19$ and $i = 65^o.3$.

The primary star is classified as an A3V star. Assuming that the primary is a normal A3V star, its expected mass is approximately 2 $M_\odot$. In conjunction with the results given in Table 8.6, then, the adopted simple model parameters are as follows:

$M_1 = 2.00\ M_\odot$

$M_2 = 0.38\ M_\odot$

$q = 0.19$

$i = 65^\circ.3$

$R = 3.48\ R_\odot$

$a = 8.207\ R_\odot$

Limb darkening coefficients of 0.54 and 0.45 were used for B and V respectively while gravity darkening coefficients of 0.87 and 0.73 were used for the primary star.

According to this model, the 42 Persei system is completely detached. The very small secondary star is consistent with the initial assumption that the variability of the system is due entirely to the primary star. This "zeroth" order model was used to provide the starting parameters in the Wilson-Devinney solution for the system.

8.5 The Wilson-Devinney Solution

The Wilson-Devinney (WD) computer code(13) is arguably the most commonly used program for the modelling of close binary systems. The results presented here were obtained using a recently completed microcomputer version of the WD code as modified by Lyder(14). The central schema of the WD code is to compare the observed light and or radial velocity curve of a binary system with a set of synthetic curves. By applying a series of differential corrections to the synthetic curves one attempts to "converge" to a statistically "best solution" for the system. To accomplish this end, the WD code consists of two sections. The LIGHT CURVE (LC) portion of the code generates synthetic light and radial velocity curves from a set of input parameters. The LC program allows the variation of up to 22 parameters including limb, gravity and reflection coefficients, inclination, mass ratio, period, radius of semimajor axis, and temperatures and potentials of the primary and secondary stars. The geometric features of the Roche model described in section 8.2 are accounted for in this model. The DIFFERENTIAL CORRECTIONS (DC) part of the code carries out the comparison between the observed data and synthetic curves. Differential corrections to pre-selected parameters are calculated. Convergence is achieved when the parameter corrections suggested by DC are smaller than their associated probable errors.

In order to use the WD code an initial solution must be constructed. The simple model of section 8.4 provided such a starting model. A preliminary solution was obtained using the LC portion of the WD code. Surface potentials for both components were adjusted until a satisfactory agreement was obtained between the observed B and V light curves and the model produced light curves. The WD-LC solution is shown in Table 8.8 while Figures 8.17 - 8.19 show the fit between the data and the WD-LC solutions in the V, B and U filters. This provided the initial parameters for an attempted solution to the differential corrections (DC) part of the WD code. Despite numerous attempts and various parameter combinations, convergence of the WD-DC parameter sets has not been achieved. The 42 Persei system is very weakly constrained, the secondary star is under-determined in this model. This is most likely due to the large disparity in the size of the two stars and very weak eclipse suggested by the solution for the system. As well, the data are still sparse at the time of secondary minimum and it is hoped that additional, high quality data of this part of the light curve will improve the convergence of the DC models.

Despite the lack of convergence encountered in running the DC portion of the program, a number of useful insights can be elicited from LC fits to the data. Figure 8.20 shows the effect that varying the orbital inclination has on the fit between the synthetic curve and the V filter data. Figure 8.21 shows the effect of varying the effective temperature of the primary star between 8700 K - 9200 K, while holding the temperature of the secondary fixed at 3500 K. Figure 8.22 demonstrates a similar effect, this time holding the primary temperature fixed (8800 K) while varying the temperature of the secondary between 3500 K and 6500 K.

It is apparent that the solution is weakly constrained by variations in the temperature of the primary but that variation of the secondary star's temperature does lead to discernible changes. The proposed "simple" model for the secondary star - $M_2 = 0.38_{\odot}$, corresponding to an M-type star - is consistent with the 3500 K best fit to the V filter curve.

Figures 8.23 - 8.25 demonstrate how tightly the potential of the primary star constrains the LC solution while variation of the potential of the secondary has relatively little effect.

All of this bolsters confidence in the simple solution offered above. The model which emerges for 42 Persei is summarized in Table 8.8.

It is also interesting to note that the LC curves which best fit the data - especially in the V and B filters - suggest a very shallow eclipse. This appears as an inflection of the LC generated light curve beginning at approximately phase 0.18 and has a depth on the order of 1 percent. .

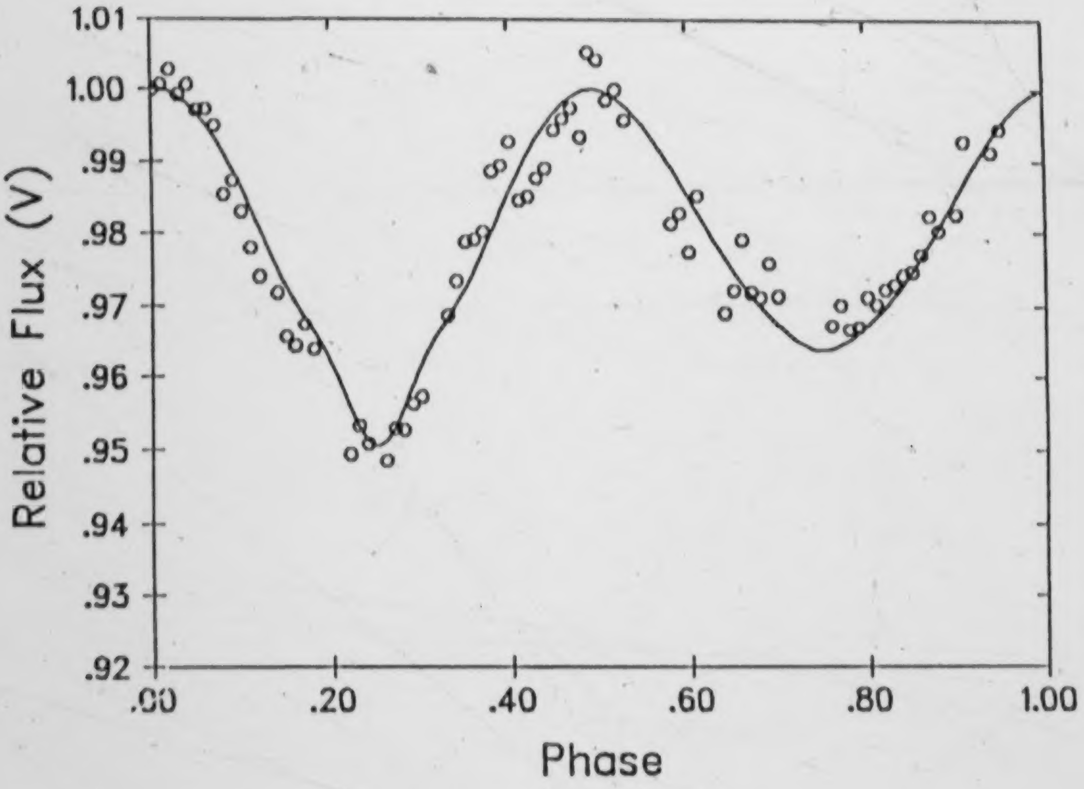

Figure 8.17 Wilson-Devinney LC solution (solid line) for the V filter compared to observations.

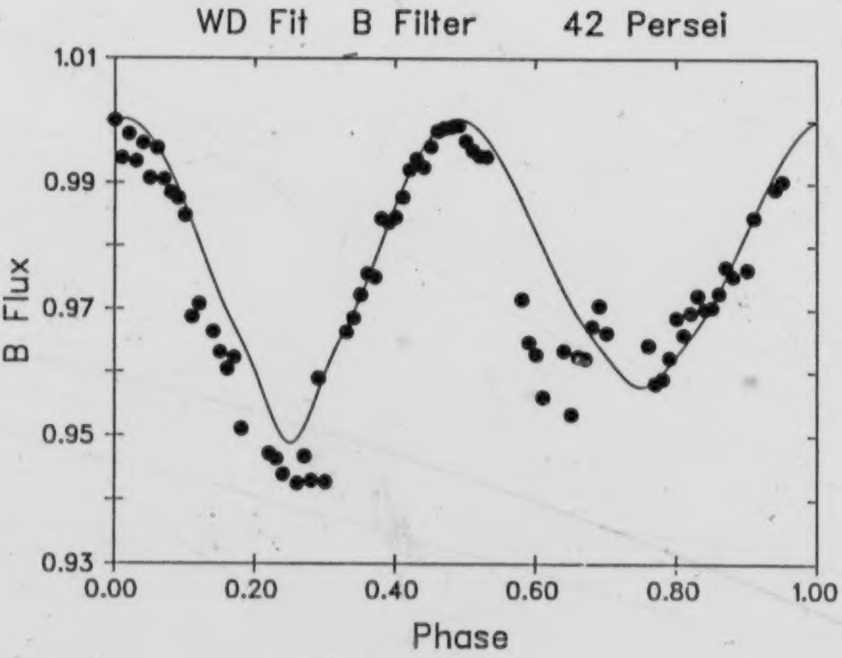

Figure 8.18 Wilson-Devinney LC solution (solid line) for the B filter compared to observations.

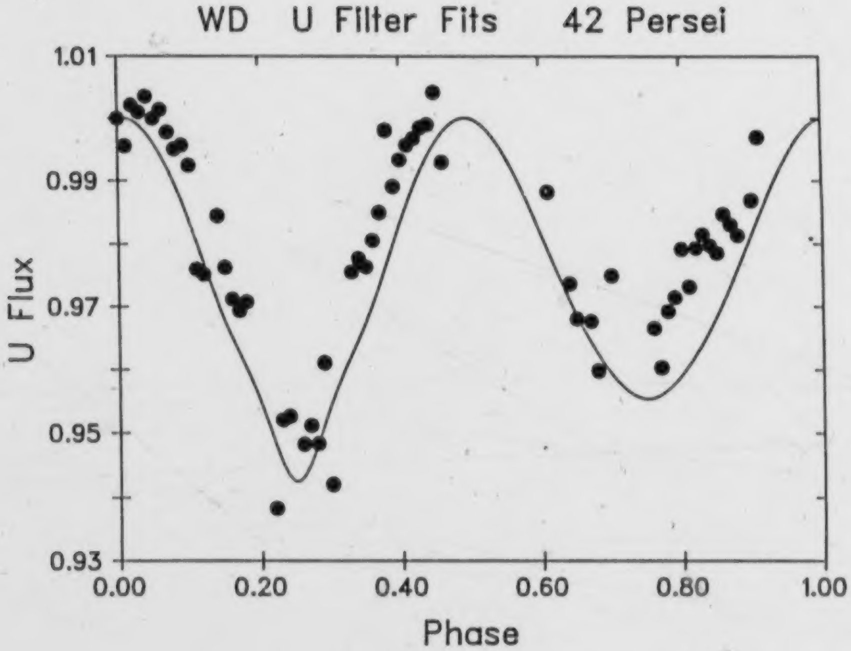

Figure 8.19 Wilson-Devinney LC solution (solid line) for the U filter compared to observations.

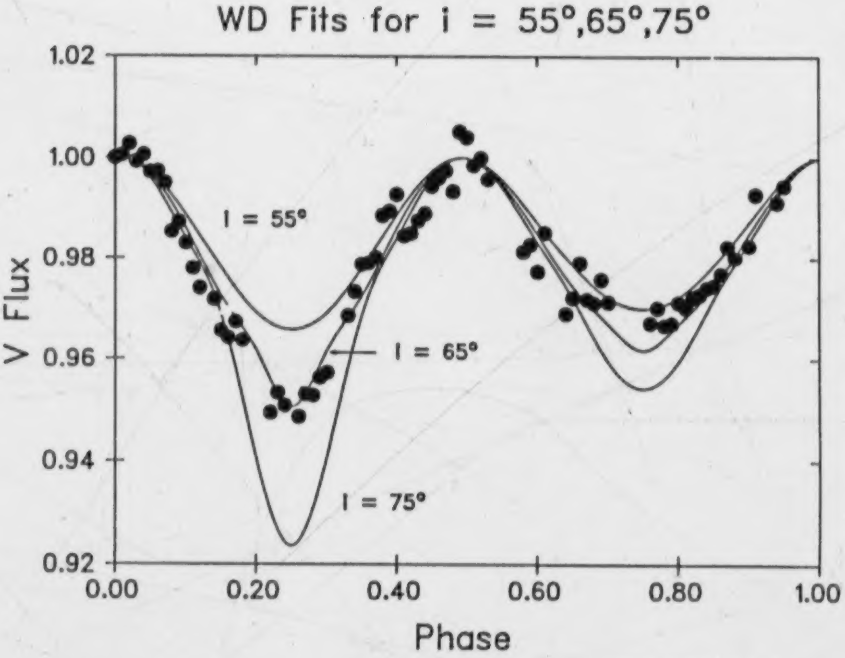

Figure 8.20 Wilson-Devinney LC solution in V filter for inclinations of 55°, 65°, and 75°. Best fit agrees with simple model value of 65°.3.

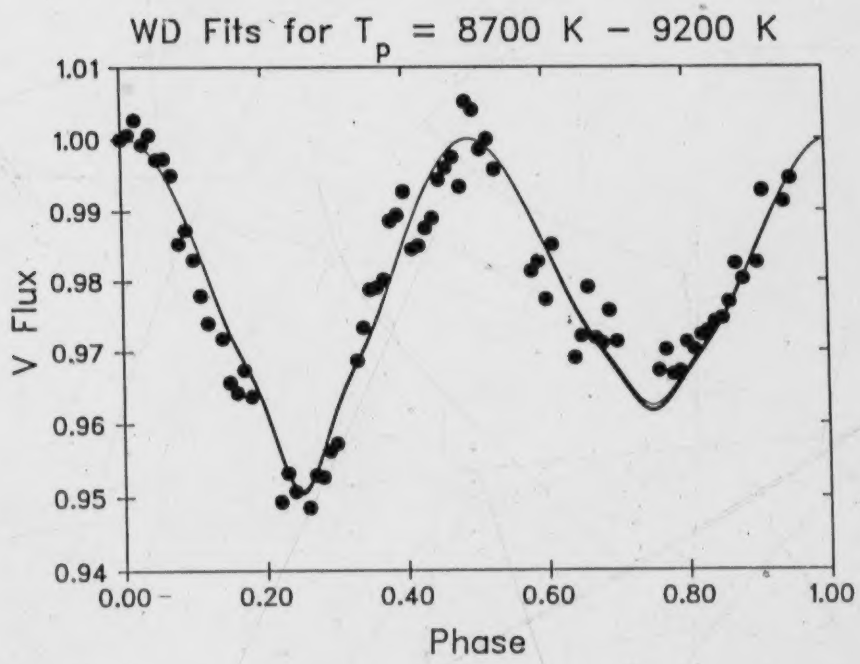

Figure 8.21 Wilson-Devinney LC solutions in V filter for primary temperatures of 8700 K, 8900 K and 9200 K. (Secondary temperature = 3500 K).

8.8 Conclusions

The ellipsoidal variability of 42 Persei has been clearly demonstrated.

One puzzling feature of the solution suggested here is the extreme mass ratio between the components. The time required for a 0.38 $M_\odot$ star to contract to the main sequence is on the order of, or may even exceed, the main sequence lifetime of a 2.0 $M_\odot$ star(15). If the secondary is a "normal" M-type star it may be possible to detect its presence spectroscopically using cross correlational techniques. We have attempted to do this but have not been successful to date(16). The analysis of spectra taken in the far red end of the spectrum would have a greater probability of detecting the secondary if, as our model suggests, it is a late type star.

The WD solution described above strongly suggests an eclipse of approximately 10 mmag depth. This should be detectable and will be pursued in the coming observing season. Detection of such an eclipse would provide indirect evidence for the low mass companion.

Our solution rests on the assumption that the two stars are tidally locked. Since, judging from the $\cos(2\theta)$ shape of the light curve, the observed variation is primarily due to ellipsoidal distortion there is evidence of tidal coupling between the stars. Consistent with 42 Persei being a tidally synchronized and distorted system, the computed orbital eccentricity listed in Table IV does not differ significantly from zero. Zahn(17) has provided time-scales for synchronization and circularization of orbits through tidal interaction. When his expressions are applied to the 42 Persei system the time-scale for orbital synchronization is less than 10^6 a while the time-scale for circularization is on the order of 2×10^7 a. The assumption of synchronous rotation is self consistent with the solution found here.

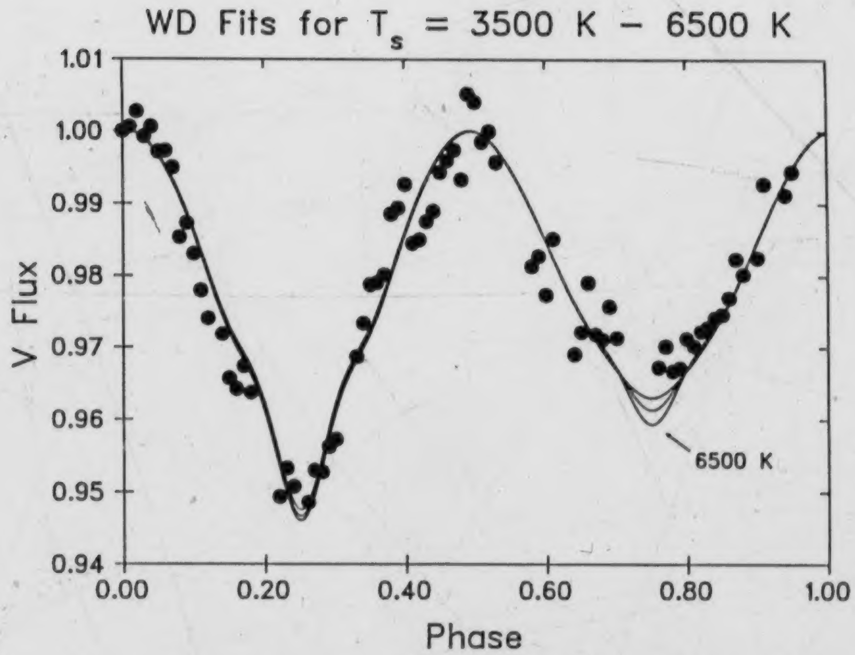

Figure 8.22 Wilson-Devinney LC solutions in V filter for secondary temperatures of 3500 K, 5500 K and 6500 K. (primary temperature = 8800 K).

Wilson-Devinney LC Solution
for 42 Persei

Element	average of V and B solutions
i	65°.3
q	0.19
T_p	8800K
T_s	3500K
Ω_p	2.70 ± 0.05
Ω_s *	4.00 ± 0.5
r_p: pole	0.40 ± 0.01
r_p: point	0.43 ± 0.01
r_p: side	0.41 ± 0.01
r_p: back	0.42 ± 0.01
r_s: pole	0.07 ± 0.02
r_s: point	0.07 ± 0.02
r_s: side	0.07 ± 0.02
r_s: back	0.07 ± 0.02

*all radii are expressed as percentages of separation between primary and secondary stars.

Table 8.8 Solution for 42 Persei based on LC output from the Wilson-Devinney code. Errors quoted express range in parameters yielding acceptable light curve fits to the data.

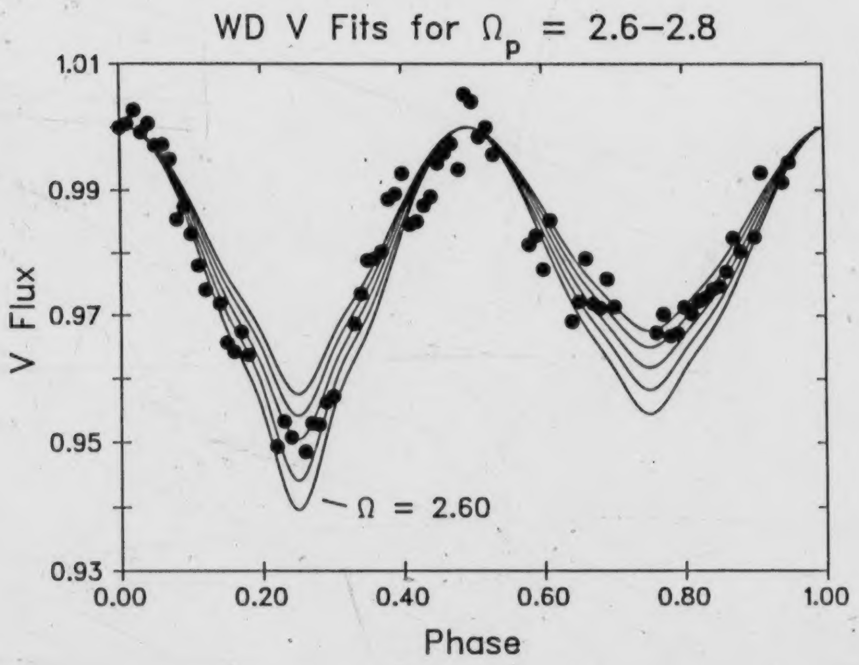

Figure 8.23 Wislon-Devinney LC solutions in V filter for primary potentials 2.60, 2.65, 2.70, and 2.80.(Secondary potential = 4.00)

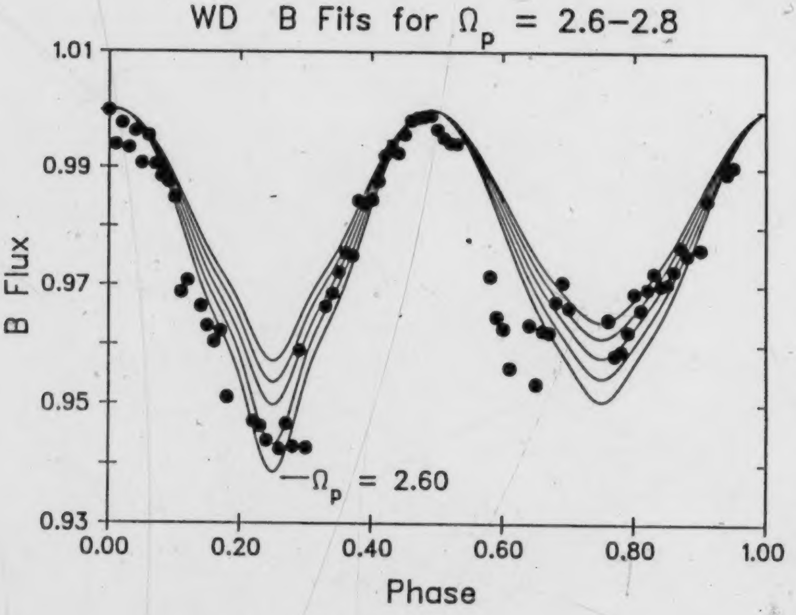

Figure 8.24 Wislon-Devinney LC solutions in B filter for primary potentials 2.60, 2.65, 2.70, and 2.80.(Secondary potential = 4.00)

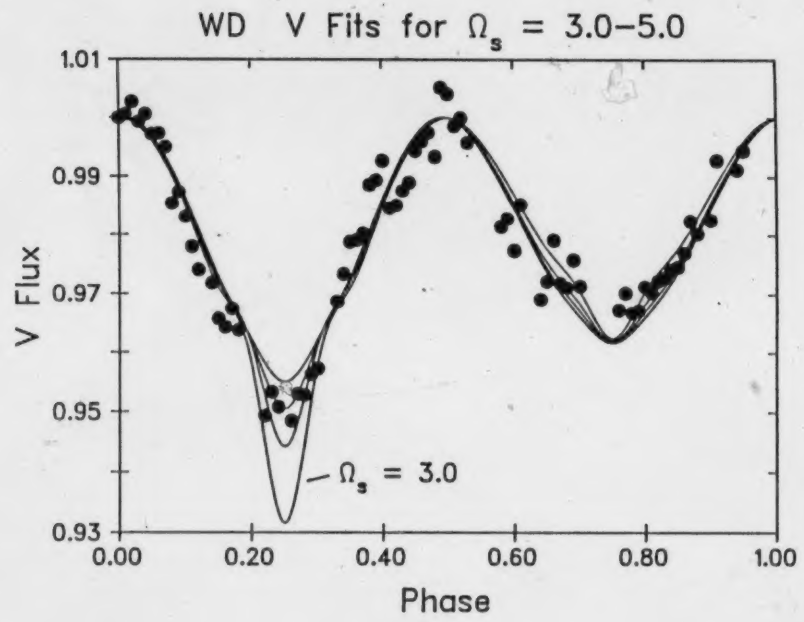

Figure 8.25 Wislon-Devinney LC solutions in V filter for secondary potentials 3.0, 3.5, 4.0, 4.5 and 5.0. (Primary potential 2.70).

Future observations on 42 Persei will concentrate on two fronts. Photometric observations will be continued to confirm or not the occurrence of a 10 mmag eclipse at primary conjunction. Further Reticon spectra will be obtained in the red region in an attempt to detect the presence of the secondary star.

Notes Chapter Eight

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11. Morris, S.L. (1983). The Ellipsoidal Variable Stars. unpublished doctoral dissertation, University of Calgary.
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Chapter Nine
Observations and Analysis of the Delta Scuti Stars HR 729 and KW 207

9.1 Introduction

The Delta Scuti stars are low amplitude pulsating stars of spectral type A through F which, on the Hertzsprung - Russell diagram, lie in an instability strip extending from slightly below the Population I main sequence to about $2^{m}.5$ above and to the right of the main sequence. They were first recognized as a distinct class of variable stars by Eggen(1) in 1956 and in the intervening period roughly one hundred members of this class have been catalogued. Most δ-Scuti stars belong to Population I and Breger(2) suggests that, next to pulsating white dwarfs, they are the most numerous group of pulsators in the Galaxy. Pulsation periods are less than $0^{d}.3$ and photometric variations are typically on the order of $0.^{m}02$. The light curves of δ-Scuti stars are often complex in nature, indicative of multiple and, in some cases, nonradial modes of oscillation.

It is the indication of nonradial modes of oscillation that confers special significance on the δ-Scuti stars and makes them an object of relevance for stellar astrophysics. Nonradial modes of oscillation depend sensitively on the interior structure of a star. Subtle changes in temperature profile or chemical composition of the stellar interior are reflected in corresponding changes in the frequencies of oscillation of the star. By carefully measuring such nonradial modes of pulsation one is provided with a powerful probe of the interior of a star. What astrophysicists(3) hope to learn from the analysis of nonradial modes of stellar oscillation is analogous to what geophysicists routinely infer from nonradial modes of oscillation of the Earth during seismic events.

9.2 The Frequency Analysis of δ-Scuti Light Curves

A typical δ-Scuti light curve will reveal a sinusoidal-like pattern with, at times, obvious modulations in amplitude from one night to the next. An accurate determination of the frequencies of oscillation present in such a light curve poses a problem of considerable difficulty for the observer. Amplitudes of variation are usually small (less than 10 mmag) and, for that reason require measurements of high photometric precision. As well, even under excellent photometric conditions, the frequency analysis of δ-Scuti light curves requires long observing sequences which are not attainable, as a rule, from a single observing site.

9.2.1 The Problem of Aliasing

Although there are several$^{(4)}$ mathematical methods for determining the frequency of a periodic signal, the most commonly used techniques are those deriving from Fourier analysis. In very simple terms, the Fourier analysis of a light curve amounts to adding together sine and cosine functions weighted by appropriate amplitudes in such a way as to reproduce the original light curve. The amplitudes of the sine and cosine terms are given, in most general terms by the expression:

$$\mathcal{F}(\nu) = \int_{-\infty}^{+\infty} f(x) e^{2\pi i \nu t} dt \qquad 9.1$$

Equation 9.1 is the Fourier transform of the function f(t) which is assumed to be a continuous function of the variable t. In practice a light curve is never known as a continuous function of time but instead as a discrete function. This leads to a modification of equation 9.2 which results in the following **discrete Fourier transform (DFT)** for f(t):

$$F_N(\nu) = \sum_{i=1}^{i=n} f(t_i) e^{2\pi i \nu t_i} \qquad 9.2$$

where N represents the number of frequencies sampled and $f(t_i)$ are the discrete measurements in the n points of the time series.

Equation 9.2 can, for computational purposes$^{(5)}$ be written as

$$F_N(\nu) = \frac{2}{n}\left(\left[\sum_{1}^{n} f(t_i)\cos(2\pi\nu t_i)\right]^2 + \left[\sum_{1}^{n} f(t_i)\sin(2\pi\nu t_i)\right]^2\right)^{1/2} \qquad 9.3$$

$$\nu = \nu_0 + N\Delta\nu \qquad 9.3a$$

The resulting expression for $F_N(\nu)$ yields a discrete set of N $[\nu, F(\nu)]$ pairs where ν is the frequency of a particular mode of oscillation and $F(\nu)$ is its corresponding amplitude. Equation 9.3a reflects the fact that the N frequencies scanned are equally spaced. In actual usage, equation 9.3 is applied to the entire data set N times to produce the $[\nu, F(\nu)]$ pairs.

If, for example, a light curve were the result of the superposition of 5 frequencies the DFT of such a curve - under ideal circumstances - would produce a discrete set of frequency - amplitude pairs of which only 5 pairs would have appreciable amplitude. This is most easily illustrated graphically.

As an example consider the following synthetic light curve:

$$l(t) = 3.0 + 0.145\cos(2\pi\cdot 6t) + 0.230\cos(2\pi\cdot 8.5t) \qquad 9.4$$

where $l(t)$ is the light curve formed by the superposition of two periodic functions of frequency 6 and 8.5 units and amplitude 0.145 and 0.23 respectively. Figure 9.1 shows the synthetic light curve $l(t)$ in the **time domain**. The modulation in the curve is evidence of the beating effect of the two cosine terms in equation 9.4. By applying equation 9.3, the light curve can be transformed from the time domain to the **frequency domain**. In the frequency domain the horizontal axis has been transformed from units of time to those of frequency (time^{-1}).

The frequency domain plot, depicted by Figure 9.2, reveals possible frequencies of variation present in the signal and indicates two strong features centered at 6.0 and 8.5 in frequency units with amplitudes of 0.143 and 0.229 units respectively.

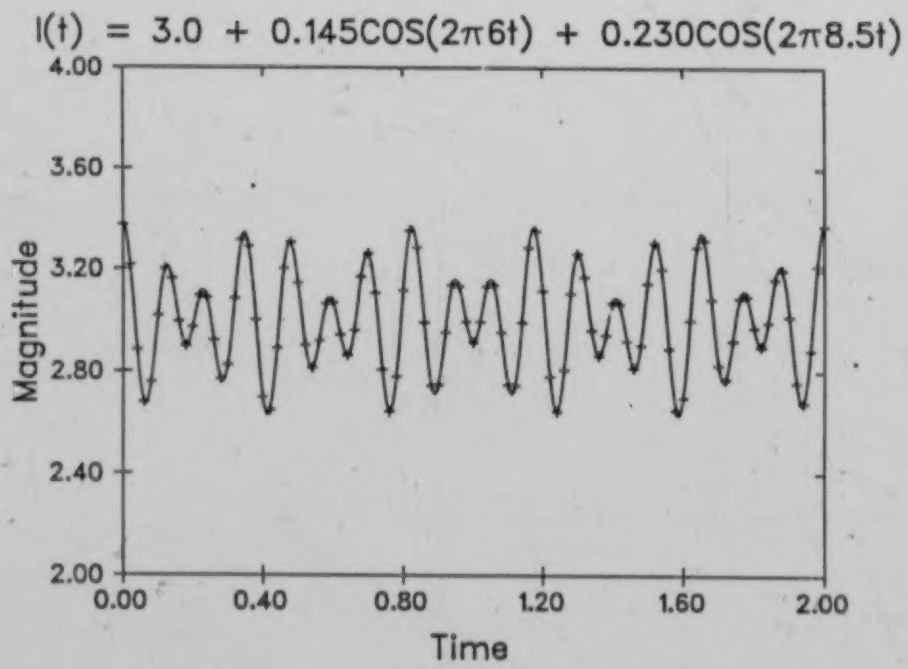


Figure 9.1 Time domain light curve for $I(t) = 3.0 + 0.145\cos(2\pi 6t) + 0.23\cos(2\pi 8.5t)$.

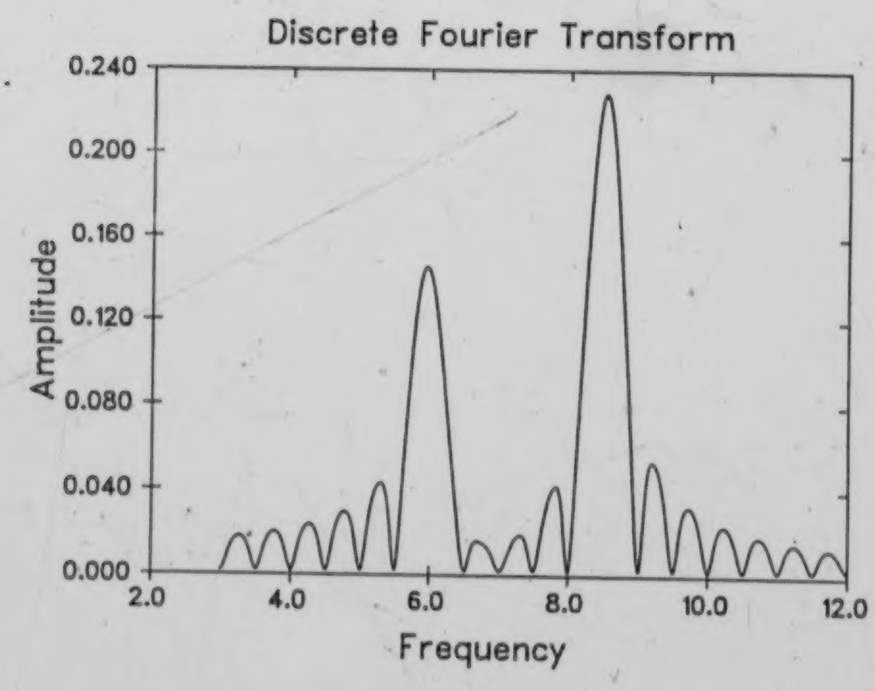


Figure 9.2 Discrete Fourier Transform of $I(t) = 3.0 + 0.145\cos(2\pi 6t) + 0.23\cos(2\pi 8.5t)$. Significant amplitudes at frequencies of 6.0 and 8.5 units are in agreement with $I(t)$.

Had l(t) been a continuous function over all t then equation 9.1 would have been used to recover the Fourier transform of the function. In that case the plot in the frequency domain would consist of two vertical spikes (δ-functions) centered at frequencies 6.0 and 8.5 units. In practice a light curve can only be sampled at a finite, discontinuous rate and for a finite span of time. Both of these limitations are reflected in the many low amplitude features visible in the Figure 9.2. Both restrictions lead, ultimately to the same effect known as **aliasing**. A physical analog to this is the interference pattern formed by light passing through a thin slit and it is the aliasing pattern in a DFT that sets the amount of useful information that can be gleaned from the transform.

If data points are collected at an equal spacing of interval Δt in time the highest frequency that can be measured in the frequency domain is set by the **Nyquist frequency** which is defined by the equation

$$\nu_{Nyquist} = \frac{1}{2\Delta t} \qquad 9.5$$

Beyond this frequency the Fourier transform is an image of the lower frequencies - analogous to higher order diffraction images in optics. For the data presented in this chapter Δt was typically 10 minutes which implies a Nyquist frequency of 72 cycles/day. If the star being studied is suspected of oscillating at rates in excess of this a shorter sampling interval - hence a possible change in observing protocol - would be needed. In the case of δ-Scuti stars the expected frequency range of interest is usually less than 30 cycles/day. This form of aliasing is relatively easy to control.

In addition to the effect of finite sampling rate, the total duration of the observations imposes another "distortion" in the frequency domain. The simple daily interruption of observations introduces what in practice turns out to be the most serious form of aliasing problem. To understand this effect one can consider the actual light curve l(t) that one obtains as being the product of a series of box functions and the "true" light curve f(t). Collectively the box functions are referred to as the **data window** for the sample and are denoted $d_w(t)$. The light curve l(t) that one obtains can be described by the following equation:

$$l(t) = f(t) \cdot d_W(t) \qquad 9.6$$

and is shown in Figure 9.3.

As Figure 9.3 shows, the data window has its own Fourier tranform which is multiplied into (ie. convolved(6) with) every feature of the Fourier transform of f(t) in the frequency domain. The Fourier transform of the data window is referred to as the **spectral window** of the data. Any periodicities in the data window will "contaminate" the resultant Fourier transform. The most dominant periodicity in a data window of observations obtained from a single observing site(7) is the daily gap in observations. This produces very strong 1 cycle/day aliases in the spectral window which contaminates the Fourier transform of the data set with numerous false (aliased) spikes. A demonstration of this is provided by Figure 9.4. In this figure a light curve has been simulated using recently published frequencies and amplitudes for the δ-Scuti star 4 Canes Venatici(8). The light curves thus produced have been "sampled" at uniform 15 minute intervals (Nyquist frequency = 48 c/d) and have been purposely contaminated by a noise level equal to 5 mmag which is representative of good quality photometric data. Table 9.1 lists these frequencies and amplitudes. The result of this numerical "experiment" can be summarized as follows:

(a) Panel 'a' depicts a continuous, 7 day data string. The spectral window is very sharp indicating very little distortion due to the Data window. The resulting Fourier transform clearly reproduces the input frequencies and amplitudes.

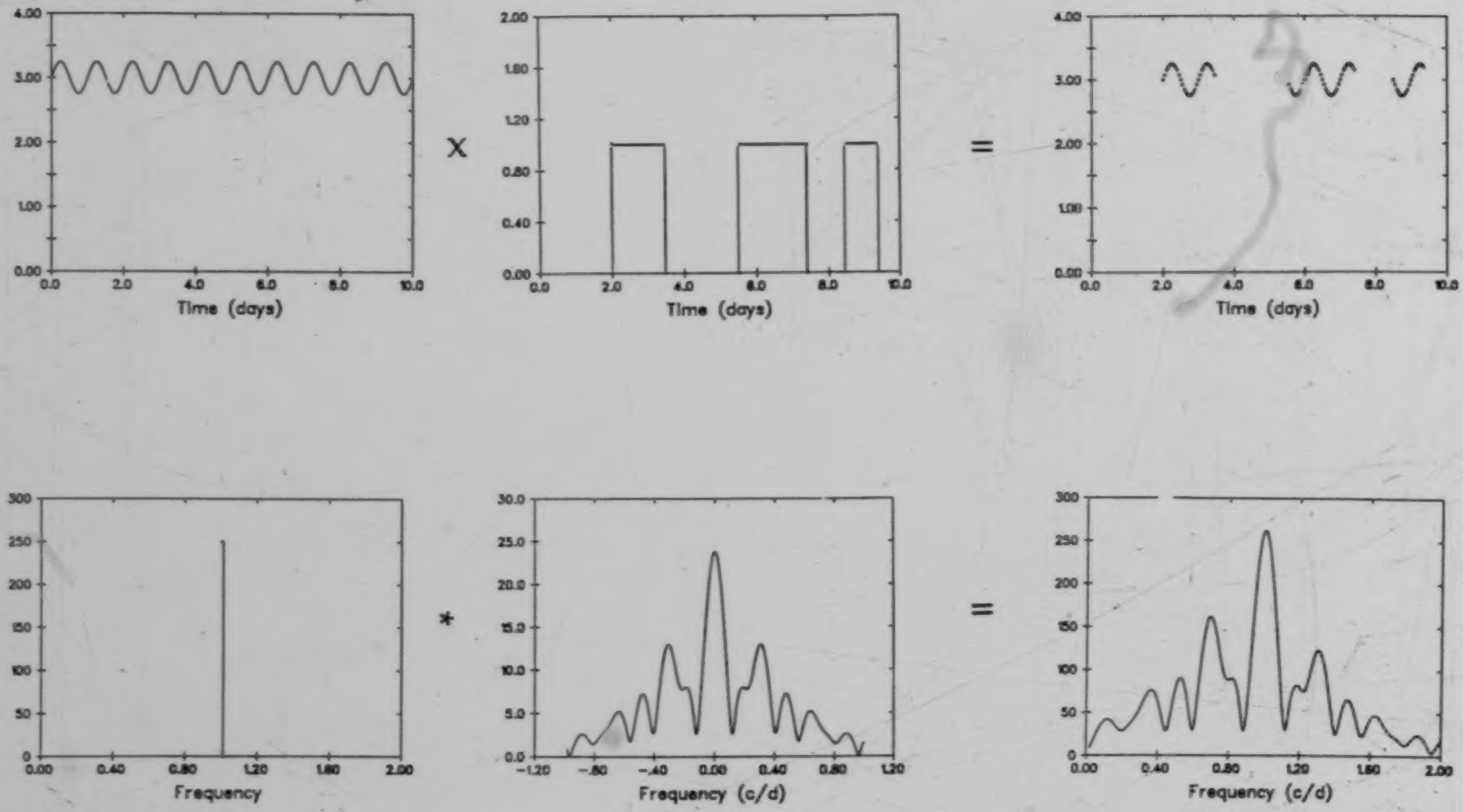


Figure 9.3 The Data windows producing an observed light curve l(t). The top panels show the data domain, those on the bottom show the frequency domain. Multiplication of light curve and data window becomes convolution of the respective Fourier transforms in the frequency domain.

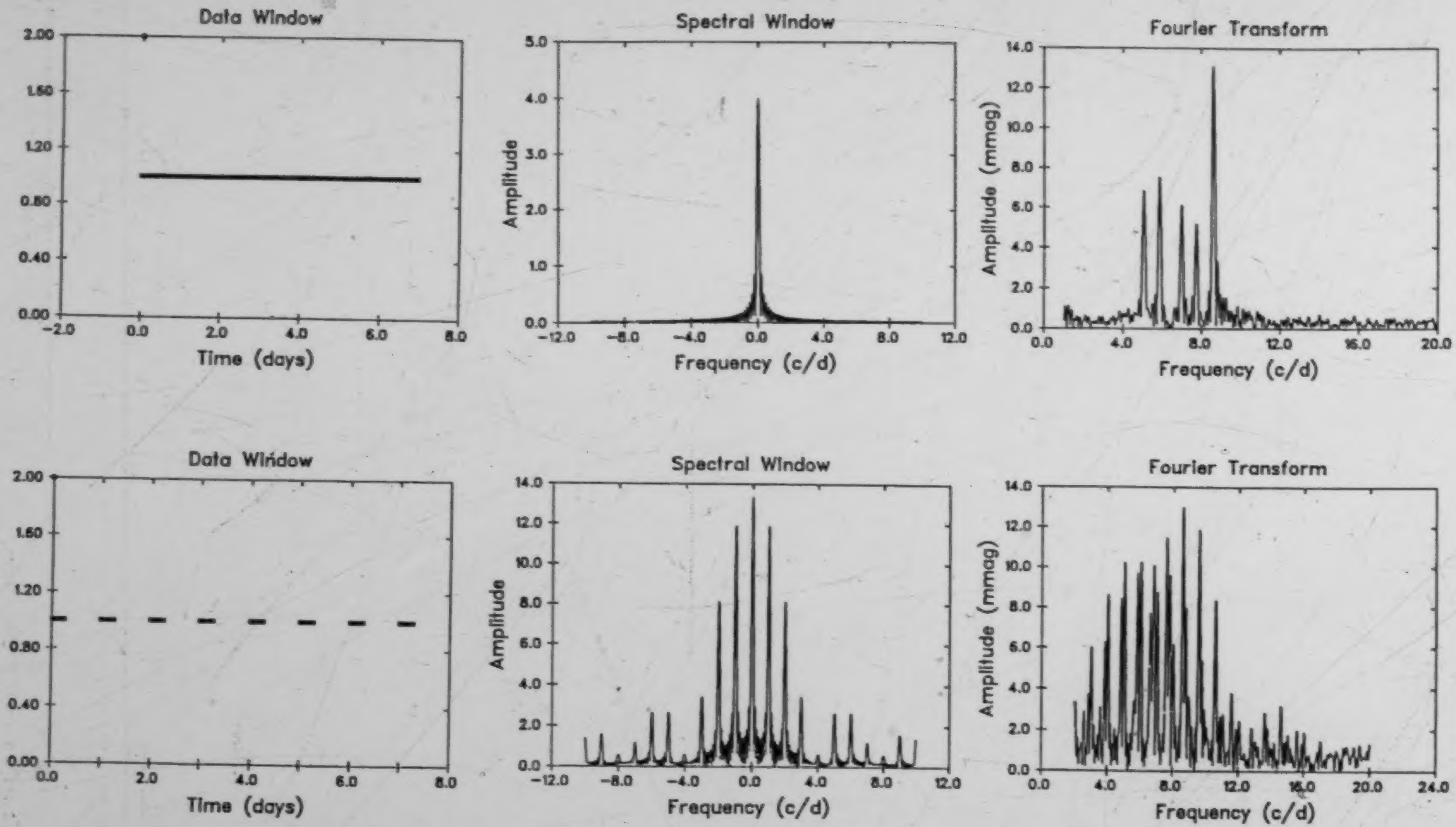


Figure 9.4 Data and Spectral Windows and Fourier transforms for light curves based on a synthesis of published frequencies for the - Scuti star 4 Canes Venatici. a: continuous data string, seven days duration. b: 7 day data string sampled at 6 hour blocks, evenly spaced. Note the extreme alias pattern .

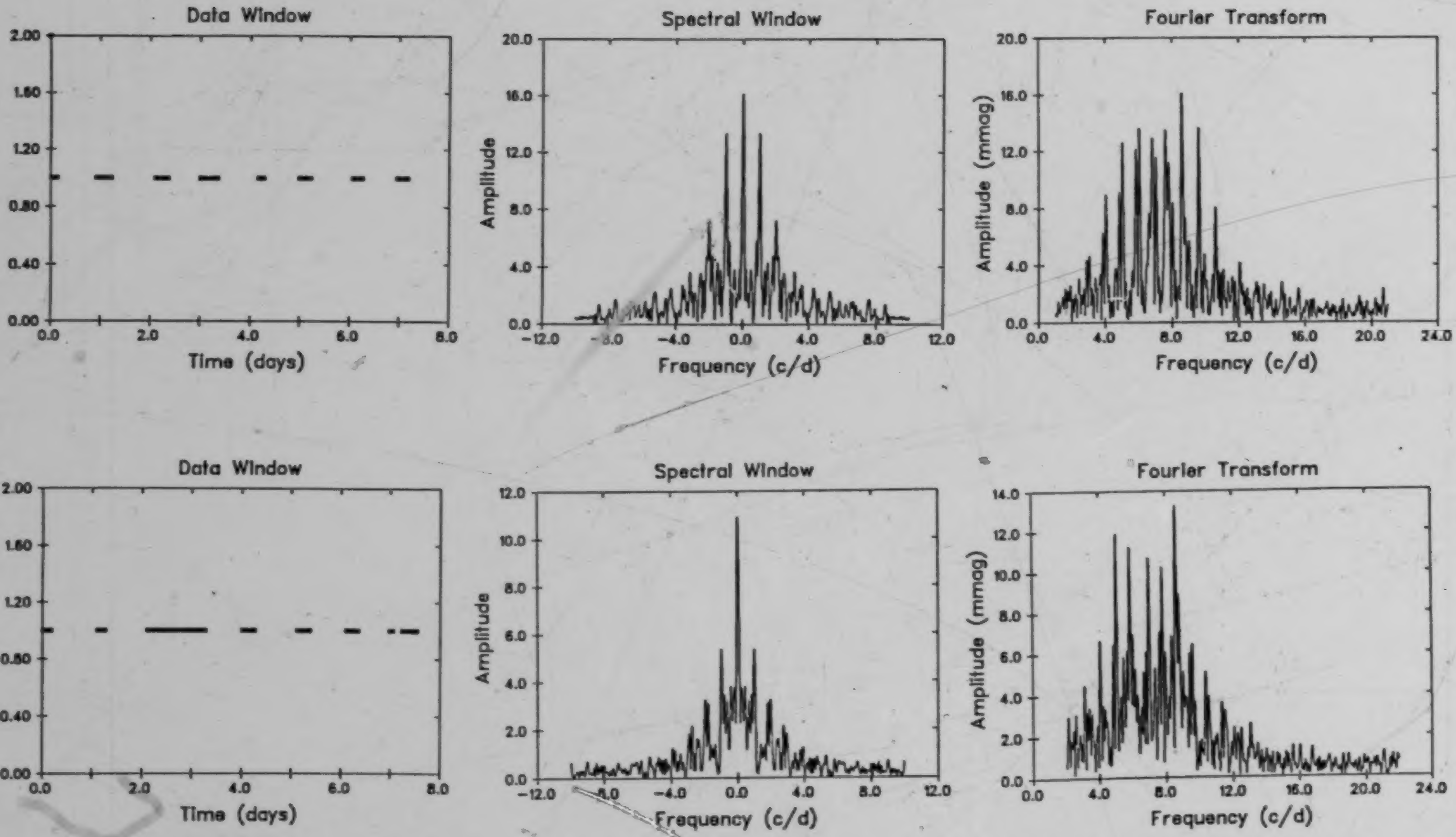


Figure 9.4 (cont.) c: 7 day data string, uneven sample blocks each day. Note the weakening side lobes in the alias pattern. d: 7 day data string with one long block exceeding one day duration. Note the drastic change in alias pattern and recovery of the principal frequency spikes in the frequency domain.

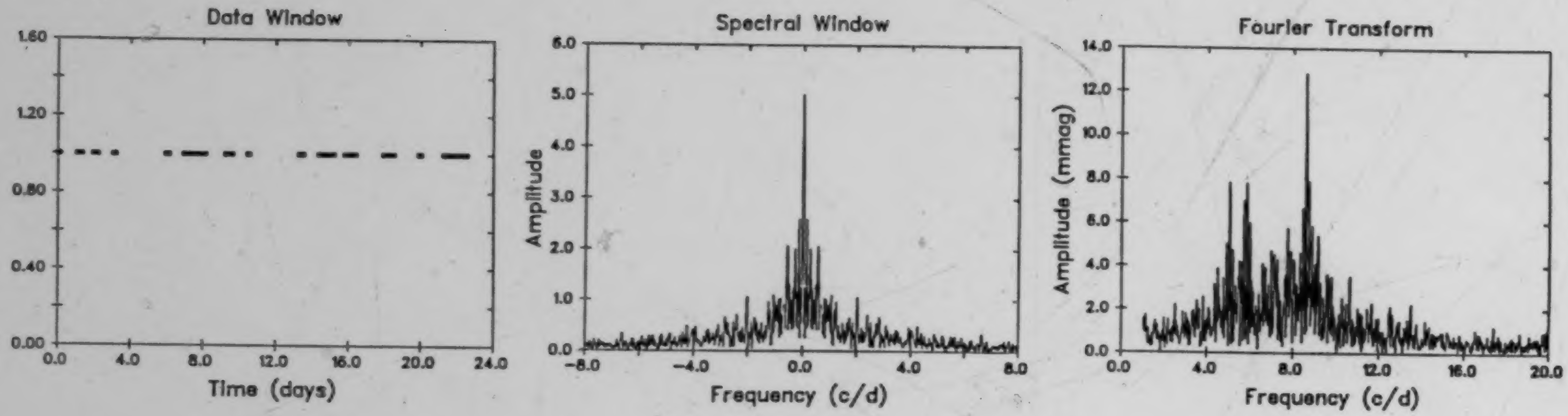


Figure 9.4 (cont.) e: 23 day data string, uneven sample blocks with several long blocks exceeding one day duration. Note the "sharpening" of the alias pattern and recovery of the frequencies and amplitudes in the frequency domain.

Pulsation Frequencies of 4 CVn (Breger et al 1989)

Frequency (c/d)	Amplitude (mmag)
f_1, 8.5950	12.8
f_2, 5.8508	7.5
f_3, 5.0475	7.7
f_4, 6.9763	5.1
f_5, 7.3778	5.2

Table 9.1 Table of frequencies and amplitudes for the δ -Scuti star 4 Canes Venatici, taken from Breger et al, October 1989.

(b) Panel 'b' shows the same data set sampled in uniform blocks of 6 hour duration. This is the worst observing protocol to adopt and the penalty for this is clearly shown by the highly aliased spectral window and very seriously distorted Fourier transform. Under such circumstances - especially with the added complication of a noisy signal - recovery of the actual frequencies and amplitudes becomes very difficult.

(c) Panel 'c' shows the 7 day data set sampled nonuniformly. The side lobes in the spectral window have been reduced but the Fourier transform is still highly distorted.

(d) Panel 'd' is similar to panels 'b' and 'c' with the exception that one data block now exceeds 1 day in duration. The side lobes in the spectral window have been significantly reduced and the input frequencies are beginning to "reappear" in the Fourier transform.

(e) Panel 'e' depicts a data set covering a total of 23 days and includes 2 long blocks each exceeding one day duration. The aliasing problem has been significantly reduced and reconstruction of the original input frequencies and amplitudes can be accomplished.

As Figure 9.4 illustrates, the aliasing pattern of the spectral window seriously compromises the Fourier transform and complicates the recovery of the true frequencies. Fortunately the spectral window can be constructed completely independent of the data itself - it is after all only a record (in the frequency domain) of the times during which obseration were made. This means that once a frequency spike has been selected the spectral window can be scaled to the amplitude of the spike in question, centered on that spike and subtracted from the frequency domain data. Any aliases of this spike will also be removed from the data. Figure 9.5 shows this process being applied to a simulated data set (based on 4 CVn). The data set covers a 20 day span and is sampled at intervals of 30 minutes in 13 irregularly spaced blocks none exceeding 6 hours duration. The topmost panel in Figure 9.5 shows the spectral window for the data set, the next panel shows the Fourier transform of the entire data set.. Subsequent panels show the removal of the alias patterns for selected frequencies. The vertical axis in each transform plot is in units of power (amplitude^2) while the horizontal axis is in units of c/d.

Table 9.2 summarizes the frequency-amplitude pairs derived from this data set employing the method described above. It is readily apparent that only the first two frequencies have been successfully recovered. Subsequent similar numerical experiments revealed that a full recovery of the entire frequency-amplitude set given in Table 9.1 occurs only when the data set contained several long blocks each in excess of one day duration (similar to the case shown in Figure 9.4e).

The implications of this simple numerical experiment are quite clear. Even with very high quality data, frequency analysis of δ-Scuti light curves from a single observing site will not, under the techniques employed here, lead to reliable recovery of the true frequencies present in the light curve. A point made by Breger(9,10) is that the reliable recovery of frequencies of δ-Scuti variability is best done in a cooperative sense by coordinating observations in international campaigns in which observers at sites distributed around the globe attempt to observe a given star on an almost continuous basis.

9.2.2 The False Alarm Criterion for Fourier Transforms

As well as the severe problems created by aliasing, noise further complicates the Fourier analysis of a light curve. What is needed is some criterion to descriminate between spectral features which arise from noise (ie. chance) and those which do not. Scargle(11) has shown that, as long as the noise in a signal is white(12) (or nearly so) a minimum threshold power z_0 (in the sense of signal to noise) can be defined such that a signal observed above this limit has only a chance p_0 of arising from noise. The detection threshold, referred to as the **false alarm threshold** is described by the following equation:

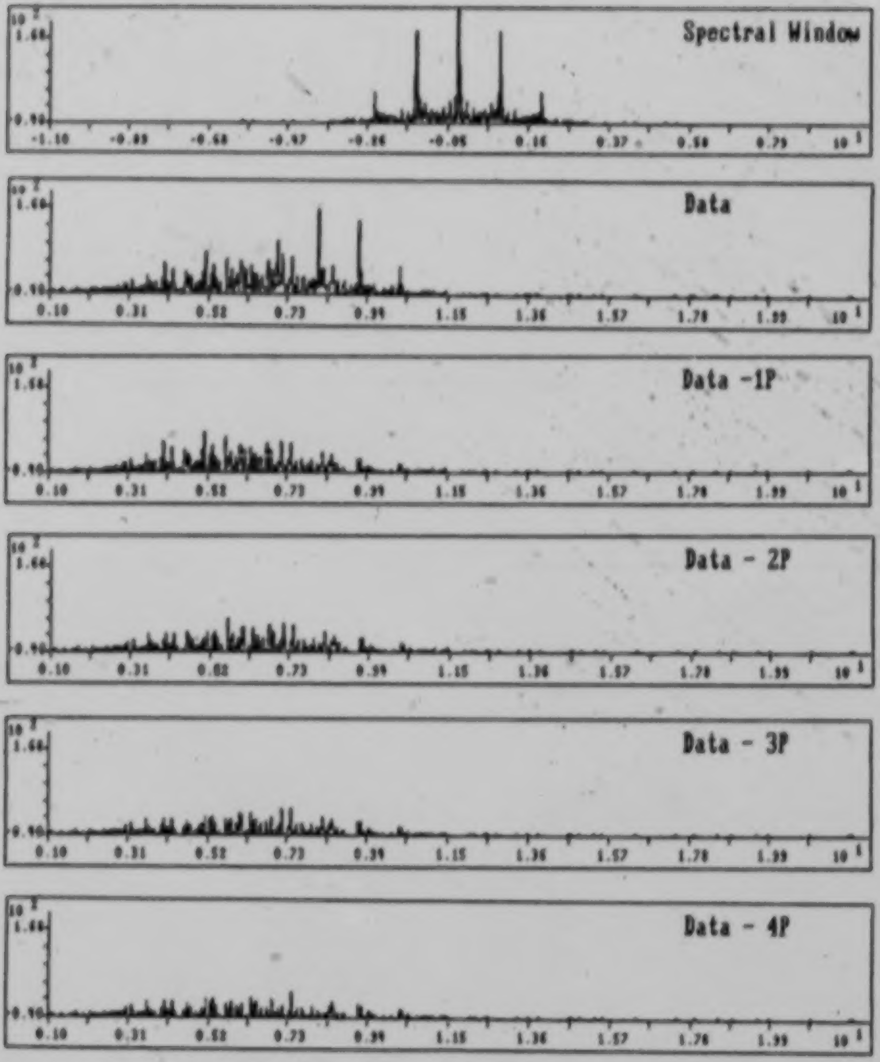


Figure 9.5 The removal of the spectral window aliases from a simulated data set based on 4 Canes Venatici. The topmost panel shows the spectral window. Next is the transform of the entire set. Subsequent panels show the result of removing features and their spectral aliases. Table 9.2 summarizes the frequency-amplitude pairs derived from this analysis.

Pulsation Frequencies of 4 CVn measured from Data Set Shown in Figure 9.2

Frequency (c/d)	Amplitude (mmag)
f_1, 8.60	11.9
f_2, 5.84	8.2
f_3, 6.38	7.5
f_4, 7.72	6.8
f_5, 7.96	6.6

Table 9.2 Table of frequencies and amplitudes for the -Scuti star 4 Canes Venatici based on a simulated data set. Comparing this set of frequency-amplitude pairs with those shown in Table 9.1 reveals that only the first two frequencies have been successfully recovered.

$$Z_0 = -\ln[1-(1-p_0)^{1/N}] \qquad 9.7$$

where N = the number of frequencies searched. Since p_0 will typically be small, equation 9.7 can be expanded as

$$Z_0 = \ln(N/p_0) \qquad 9.8$$

For the data to be presented in the present chapter $p_0 = 0.01$. Thus the power signal to noise level for 99% confidence is given by

$$Z_0 = 4.6 + \ln(N) \qquad 9.9$$

This can be related to a false alarm threshold amplitude by the equation

$$X = (Z_0/N_0)^{1/2} \cdot 2\sigma \qquad 9.9a$$

where N_0 is the number of data points in the light curve and is the standard deviation of the data.

Scargle's original formulation of the false alarm criterion was based on the assumption that only one frequency was present in the time series and Fourier transform. As Matthews et al$^{(13)}$ indicate, if more than one frequency is present in the signal the resulting value for z_0 will be elevated which will in turn imply an overestimation of the false alarm level.

It is important to appreciate what the false alarm level does and does not indicate. First, any signal detected above the false alarm amplitude should not, therefore, be considered to be a "true" signal. Such a signal may still be the alias of another signal. What the false alarm criterion does say is that such a signal will have a probability less than p_0 of arising from chance. Similarly, signals below the false alarm level cannot be rejected outright - there can be true signals at levels less than the false alarm level. Such signals, however, will have a greater chance of being accompanied by spurious signals arising solely from chance, and the recovery of signals less than the false alarm level becomes a dubious process.

Meaningful analysis of δ-Scuti light curves is far from trivial and certainly more than a matter of merely collecting high quality data. The use of Fourier techniques is fraught with many potential pitfalls - especially when analysing data from a single observing site. Before proceeding to a discussion of the two δ-Scuti stars HR 729 and KW 207 it is good to consider a comment by J. W. Tukey - an acknowledged expert in the field of time series analysis:

> [when referring to spectral analysis of time series] spectral can refer to either spectra or spectres!(14)

9.3 The International Campaigns on HR 729 and KW 207

During the months of November 1988 and February 1989 the author participated in international campaigns to observe the δ-Scuti stars HR 729 and KW 207. The frequency analysis to be given for each star, in light of comments made in the previous section, should be viewed as only tentative. A full analysis of these stars will require several years of such collaborative efforts. Participating observatories in these campaigns are: Beijing Astronomical Observatory (People's Republic of China), Konkoly Observatory (Hungary), Sierra Nevada Observatory (Spain) and the Devon Astronomical Observatory (Canada).

9.3.1 The Campaign on HR 729

The δ-Scuti star HR 729 (= HD 15550 = UU ARI = 26 ARI, $\alpha(2000) = 2^h30^m37^s$, $\delta(2000) = +19°51'21''$) is a low amplitude variable of mean V magnitude = 6.2. The star was chosen for the campaign because of its high rotational velocity of vsini = 152 km/s. Limited data(15) on this star suggest that it pulsates with two frequencies of approximately 13.5 c/d and 21.3 c/d. The campaign on HR 729 ran from October 30, 1988 to November 22, 1988. Throughout the campaign the stars HR 646 = C1 (F5 V, V = 5.3) and HR 741 = C2 (F8 V, V = 6.0) were used as comparison stars.

9.3.1.1 Observing Protocol for HR 729

All observations were made in the Johnson V filter and consisted of averages of 3, 20 s integrations each in the sequence C1 - V - C2. Sky corrections were made as necessary and standard methods of reduction (see chapter 8) were employed throughout. Table 9.3 summarizes the reduced data for the entire campaign and presents the heliocentric Julian date for each observation and the V-C1, V-C2 and C2-C1 differential magnitudes. Figures 9.6 - 9.8 show the V filter light curves for V-C1, V-C2 and C2-C1. Table 9.4 presents a journal for the campaign observations as well as the zero point averages and standard deviations over the course of the campaign.

9.3.1.2 Frequency Analysis for HR 729

Figures 9.6 and 9.7 clearly reveal the variability of HR 729. As well, the night to night variations in the light curves suggest that there are several modes present. Fourier transforms were computed for V-C1, V-C2 and C2-C1. A total of 1000 frequencies in the range 0 - 40 c/d were sampled and using the data supplied in Table 9.4, a mean false alarm level of $A_{99\%}$ = 4.1 mmag was adopted. The Fourier transforms for V-C1 and V-C2 in the range 8 - 32 c/d are shown in Figure 9.9. It is apparent that while there are many features present, most lie below the 99% confidence level. Because of this the strategy employed to extract frequency information was to accept as possible candidate frequencies only those frequencies which appeared in both V-C1 and V-C2. Any frequencies appearing in all three sets were rejected as signal contamination. One likely source of such contamination would arise from systematic shifts in the zero points of the observations between successive nights. The C2-C1 column in Table

9.4 gives some indication that this is occurring and would lead to low frequency noise contamination in the V-C1 and V-C2 transforms.

Figures 9.10 - 9.12 show the spectral window and transforms for the V-C1, V-C2 and C2-C1 data sets. The spectral window removal technique described in section 9.2.1 was applied in each case. The frequencies measured for each data set are summarized in Table 9.5. Three possible frequencies emerge from this analysis and are listed in Table 9.5. Given the limitations of single observing site, highly aliased data, these frequencies can only be viewed as provisional - although the feature centered at 17.35 c/d is likely close to a true frequency of oscillation. As well, it is encouraging that the frequencies found are in the range suggested by Breger at the beginning of the campaign.

If one has a series of frequency-amplitude pairs it should be possible to reproduce the original light curve. This has been attempted in the case of the V-C1 light curve. A three term cosine series of the form

$$I(t) = A_0 + \sum_{i=1}^{i=3} A_i \cos(2\pi f_i t) \tag{9.10}$$

was constructed where A_0 is the mean amplitude for V-C1 (Table 9.4) and the A_i, f_i terms are those given in Table 9.5. Figure 9.13 shows the fit between this curve and the data. Although many of the features of the V-C1 light curve are reproduced there are still some "rough" areas - especially the data from the night of November 8 (MST, JD = 2447474+). The failure to recover the extreme minima or maxima in the data suggests that there is at least one unaccounted for frequency-amplitude pair.

HJD	V-C1	V-C2	C2-C1	HJD	V-C1	V-C2	C2-C1	HJD	V-C1	V-C2	C2-C1
2447465.6903	0.8549	0.0956	0.7592	2447474.7412	0.8658	0.0846	0.7813	2447486.7409	0.8691	0.0831	0.7859
2447465.6996	0.8670	0.0954	0.7716	2447474.7450	0.8669	0.0865	0.7803	2447486.7468	0.8705	0.0787	0.7919
2447465.7057	0.8653	0.0975	0.7678	2447474.7491	0.8645	0.0842	0.7803	2447486.7513	0.8705	0.0792	0.7913
2447465.7103	0.8685	0.1008	0.7677	2447474.7542	0.8637	0.0839	0.7798	2447486.7551	0.8690	0.0823	0.7866
2447465.7263	0.8574	0.0851	0.7723	2447474.7588	0.8653	0.0855	0.7798	2447486.7591	0.8647	0.0813	0.7834
2447465.7345	0.8587	0.0885	0.7702	2447474.7628	0.8682	0.0852	0.7831	2447486.7626	0.8642	0.0791	0.7851
2447465.7433	0.8846	0.1114	0.7732	2447474.7669	0.8677	0.0858	0.7819	2447486.7671	0.8668	0.0787	0.7881
2447465.7489	0.8760	0.1035	0.7724	2447474.7711	0.8666	0.0853	0.7813	2447486.7707	0.8654	0.0836	0.7818
2447465.7535	0.8768	0.0998	0.7770	2447474.7752	0.8691	0.0899	0.7792	2447486.7752	0.8705	0.0858	0.7846
2447465.7587	0.8735	0.0855	0.7880	2447474.7796	0.8667	0.0869	0.7798	2447486.7847	0.8722	0.0896	0.7826
2447473.6945	0.8757	0.1041	0.7716	2447474.7836	0.8726	0.0902	0.7824	2447486.7915	0.8692	0.0843	0.7849
2447473.7011	0.8759	0.1053	0.7706	2447474.7873	0.8665	0.0887	0.7779	2447486.7955	0.8700	0.0902	0.7798
2447473.7061	0.8741	0.0978	0.7764	2447474.7915	0.8691	0.0922	0.7768	2447486.8000	0.8732	0.0896	0.7836
2447473.7107	0.8685	0.0950	0.7736	2447474.7955	0.8710	0.0868	0.7842	2447486.8036	0.8685	0.0855	0.7830
2447473.7151	0.8658	0.0926	0.7731	2447475.6088	0.8737	0.1048	0.7689	2447486.8085	0.8646	0.0840	0.7806
2447473.7193	0.8630	0.0904	0.7726	2447475.6138	0.8587	0.0906	0.7681				
2447473.7239	0.8574	0.0843	0.7731	2447475.6184	0.8611	0.0905	0.7706				
2447473.7286	0.8611	0.0871	0.7739	2447475.6223	0.8597	0.0979	0.7619				
2447473.7331	0.8613	0.0887	0.7726	2447475.6267	0.8632	0.0981	0.7651				
2447473.7916	0.8658	0.0922	0.7735	2447475.6310	0.8575	0.0880	0.7695				
2447473.7956	0.8650	0.0902	0.7748	2447475.6355	0.8475	0.0852	0.7623				
2447473.7997	0.8633	0.0914	0.7719	2447475.6402	0.8537	0.0864	0.7673				
2447473.8043	0.8625	0.0902	0.7723	2447475.6438	0.8584	0.0941	0.7643				
2447473.8085	0.8678	0.0918	0.7760	2447475.6482	0.8626	0.0907	0.7720				
2447473.8129	0.8699	0.0920	0.7779	2447475.6523	0.8627	0.0923	0.7704				
2447473.8168	0.8721	0.0953	0.7768	2447475.6563	0.8665	0.0994	0.7671				
2447473.8208	0.8727	0.0983	0.7744	2447475.6613	0.8644	0.0975	0.7670				
2447473.8253	0.8675	0.0963	0.7712	2447475.6651	0.8698	0.1022	0.7676				
2447473.8293	0.8659	0.0924	0.7735	2447475.6690	0.8695	0.0961	0.7734				
2447473.8333	0.8678	0.0942	0.7736	2447475.6727	0.8704	0.0939	0.7766				
2447473.8376	0.8741	0.0918	0.7823	2447475.6785	0.8644	0.0854	0.7790				
2447473.8417	0.8490	0.0947	0.7543	2447475.6829	0.8594	0.0877	0.7717				
2447474.5936	0.8647	0.0780	0.7866	2447475.6876	0.8541	0.0811	0.7730				
2447474.5983	0.8616	0.0762	0.7854	2447475.6917	0.8541	0.0773	0.7768				
2447474.6027	0.8583	0.0738	0.7845	2447475.6965	0.8635	0.0882	0.7753				
2447474.6078	0.8615	0.0734	0.7882	2447475.7026	0.8703	0.0942	0.7761				
2447474.6123	0.8725	0.0792	0.7933	2447475.7074	0.8766	0.1049	0.7717				
2447474.6168	0.8773	0.0905	0.7867	2447475.7125	0.8734	0.0994	0.7740				
2447474.6213	0.8716	0.0865	0.7851	2447475.7177	0.8685	0.0906	0.7779				
2447474.6254	0.8772	0.0852	0.7919	2447475.7225	0.8661	0.0913	0.7748				
2447474.6297	0.8829	0.0978	0.7851	2447475.7259	0.8662	0.0937	0.7725				
2447474.6345	0.8739	0.0905	0.7834	2447475.7329	0.8656	0.0930	0.7725				
2447474.6399	0.8692	0.0909	0.7782	2447475.7373	0.8683	0.0969	0.7713				
2447474.6449	0.8791	0.0929	0.7862	2447475.7417	0.8645	0.0922	0.7722				
2447474.6492	0.8747	0.0911	0.7837	2447475.7458	0.8648	0.0941	0.7708				
2447474.6537	0.8707	0.0854	0.7852	2447475.7495	0.8655	0.0935	0.7720				
2447474.6578	0.8689	0.0829	0.7859	2447475.7536	0.8614	0.0904	0.7710				
2447474.6624	0.8776	0.1020	0.7756	2447475.7592	0.8607	0.0908	0.7699				
2447474.7330	0.8670	0.0659	0.8011	2447475.7713	0.8750	0.1054	0.7696				
2447474.7369	0.8647	0.0824	0.7824	2447475.7754	0.8577	0.0873	0.7704				

Table 9.3 Summary of data for the δ-Scuti variable HR 729 and the comparison stars HR 646 and HR 741. All observations are in the Johnson V filter.

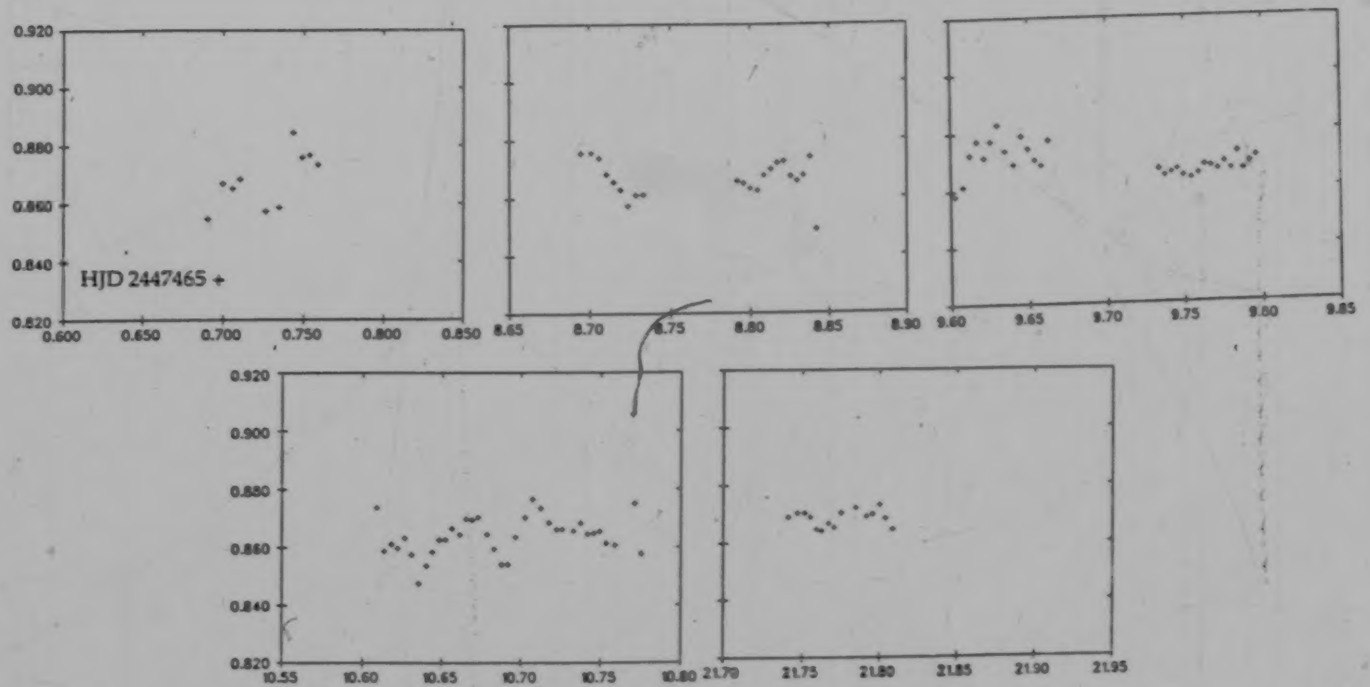


Figure 9.6 HR 729 - HR 646 (V - C1) plots for the November campaign on HR 729. All plots are in the Johson V filter.

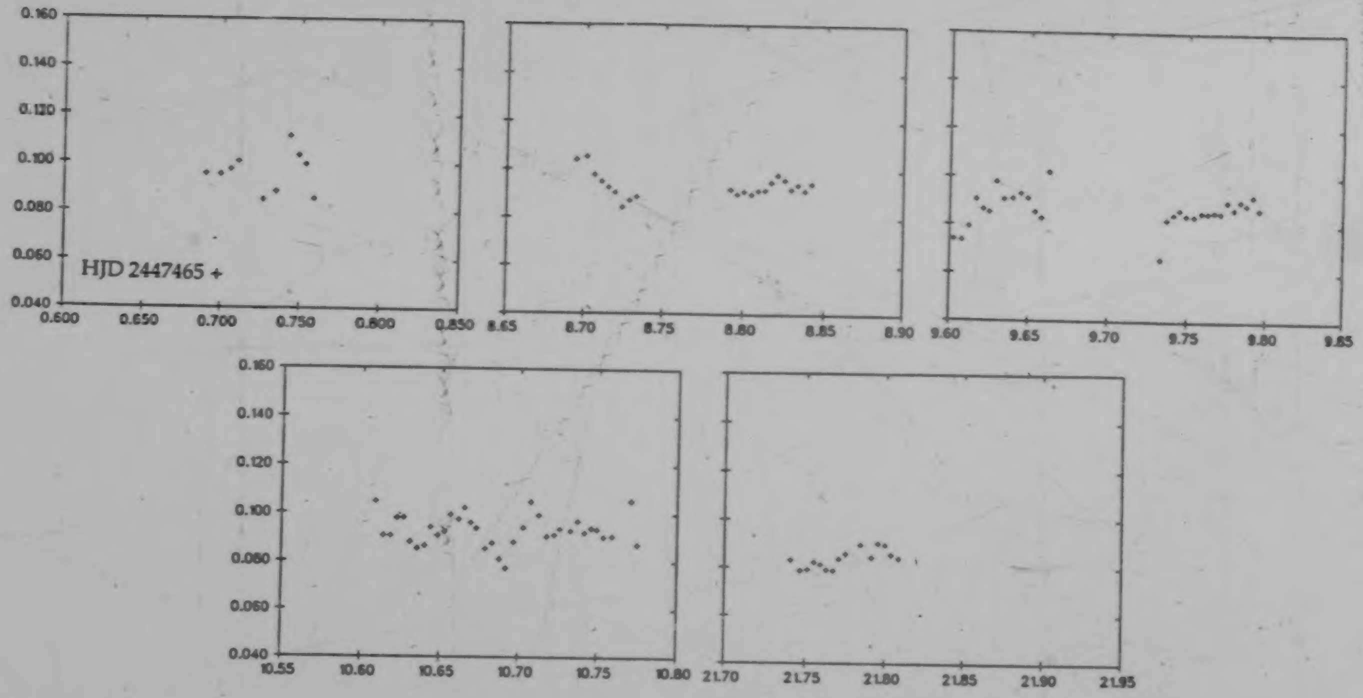


Figure 9.7 HR 729 - HR 741 (V - C2) plots for the November campaign on HR 729. All plots are in the Johson V filter.

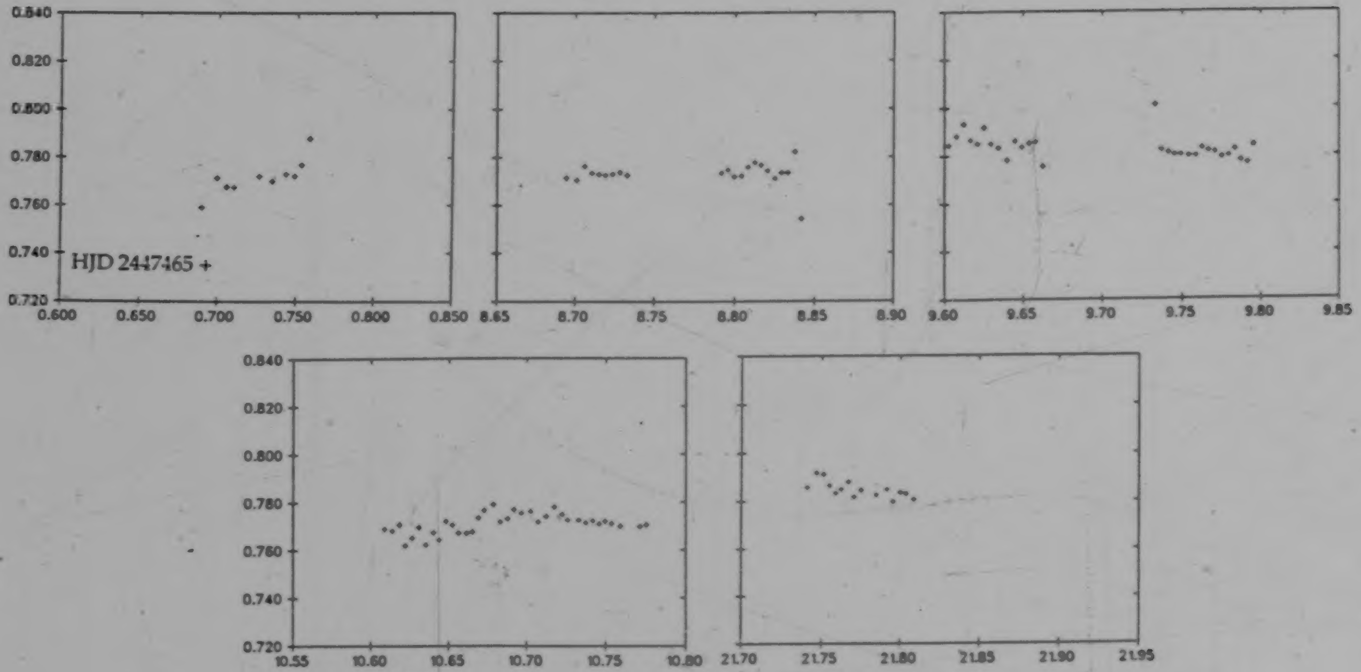


Figure 9.8 HR 741 - HR 646 (C2 - C1) plots for the November campaign on HR 729. All plots are in the Johson V filter.

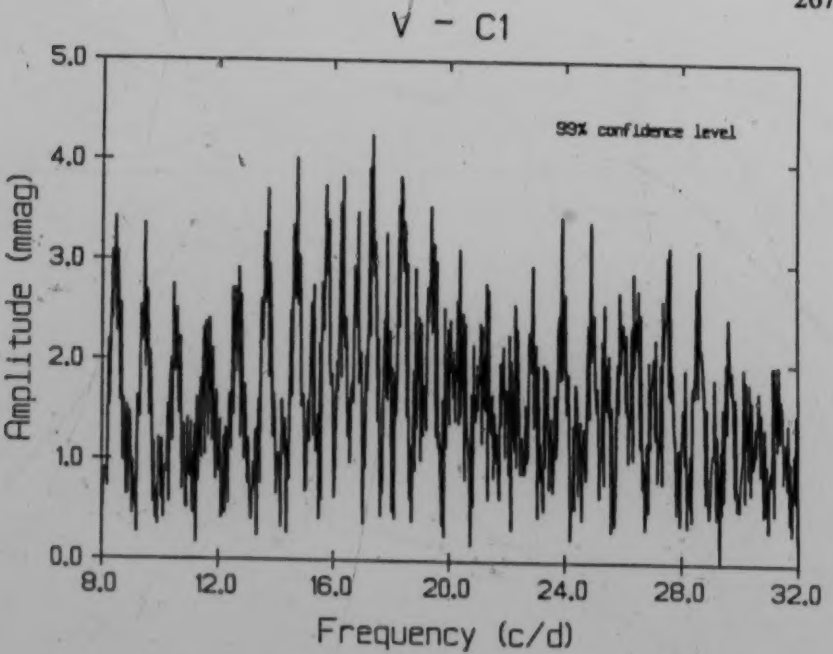
Journal of Observations
HR 729 October 30 - November 22 /1988

Date	V-C1 V Mag	σ V Mag	V-C2 V Mag	σ V Mag	C2-C1 V Mag	σ V Mag
Oct 30	0.8683	0.0091	0.0963	0.0079	0.7719	0.0070
Nov 7	0.8666	0.0063	0.0935	0.0048	0.7731	0.0048
Nov 8	0.8693	0.0055	0.0856	0.0070	0.7836	0.0050
Nov 9	0.8639	0.0064	0.0929	0.0062	0.7710	0.0040
Nov 20	0.8686	0.0027	0.0837	0.0038	0.7849	0.0034

zero point average			
V Mag	0.8673	0.0904	0.7769
σ	0.0019	0.0049	0.0061
Total set			
Average	0.8669	0.0901	0.7768
σ	0.0065	0.0075	0.0077

total number of observations $N_0 = 114$

Table 9.4 Journal of observations for November 1988 campaign on HR 729.



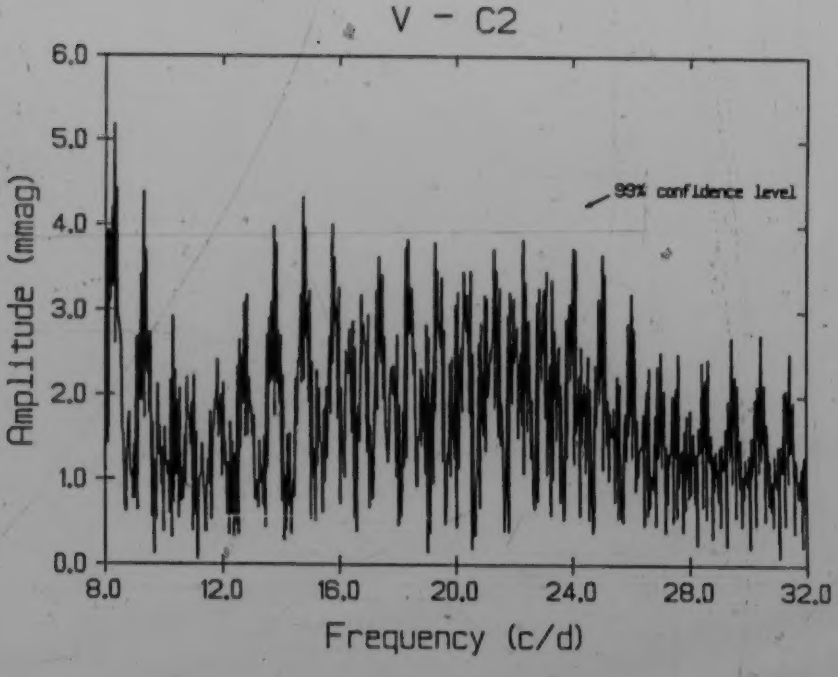


Figure 9.9 Fourier transforms of V-C1 and V-C2 data for the HR 729 campaign, November 1988.

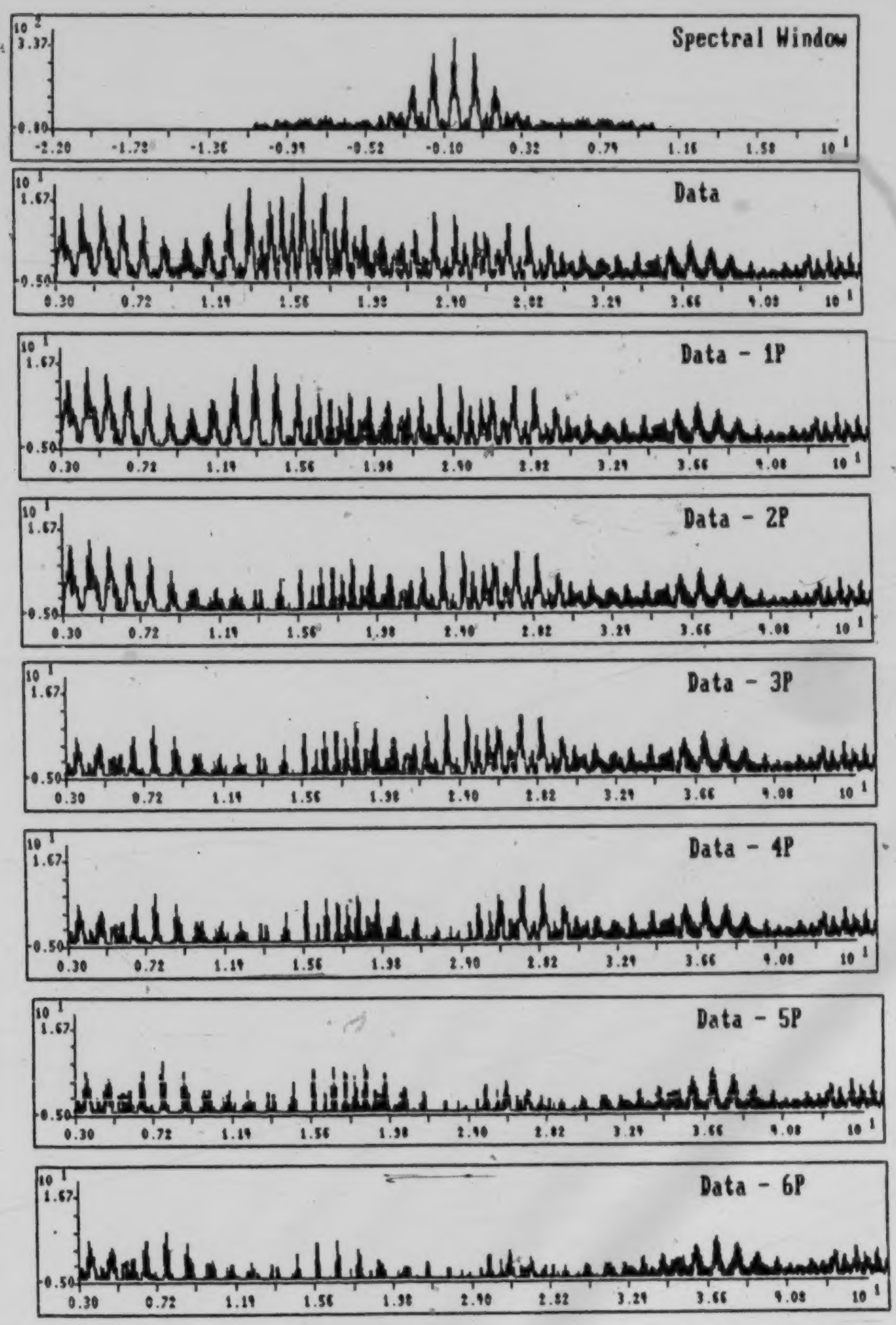


Figure 9.10 Spectral window and removal of prominent spectral features from the V-C1 Fourier transform. Vertical axis measured in units of power (mmag^2). Frequency span 0-40 c/d.

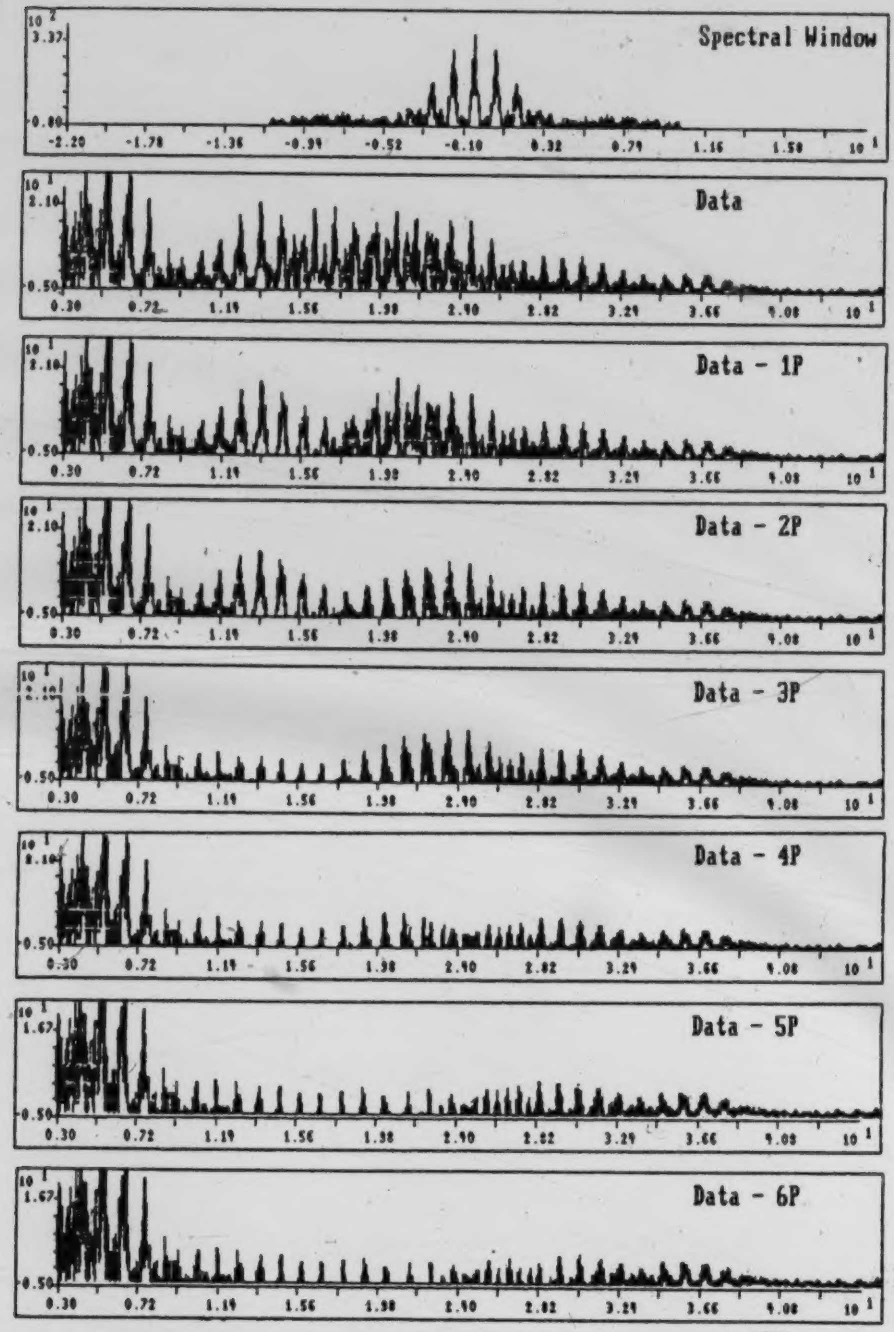


Figure 9.11 Spectral window and removal of prominent spectral features from the V-C2 Fourier transform. Vertical axis measured in units of power ($mmag^2$). Frequency span 0-40 c/d.

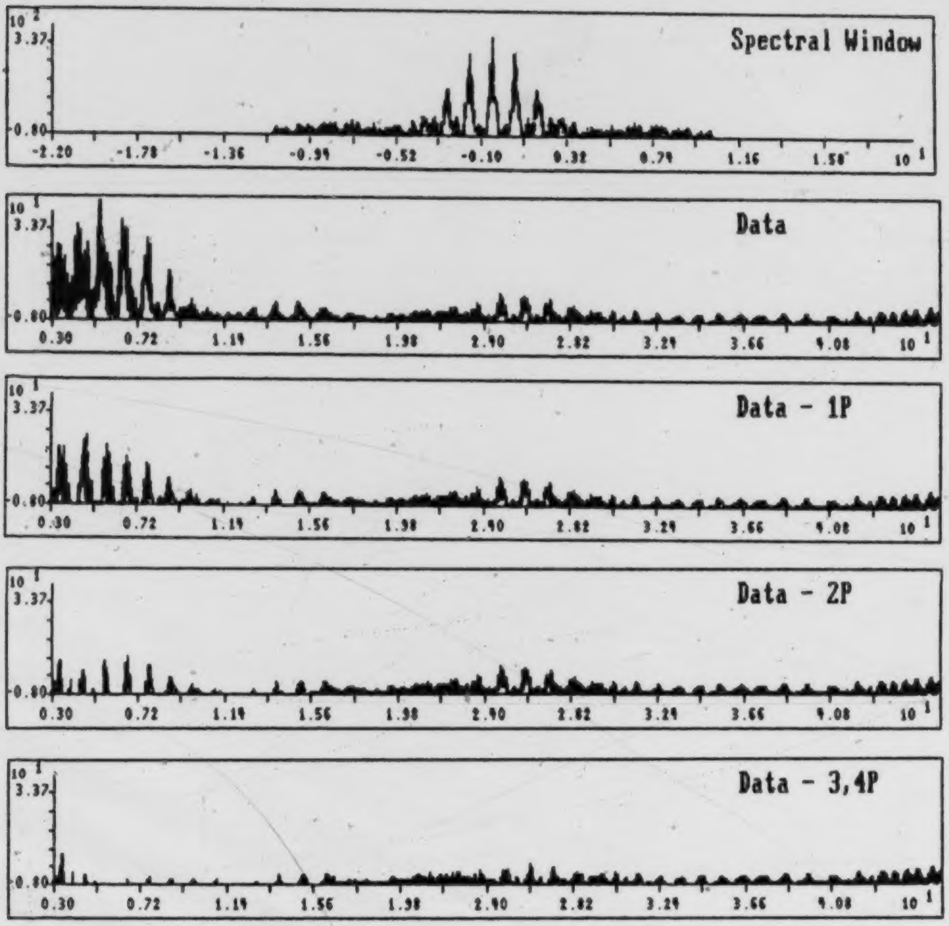


Figure 9.12 Spectral window and removal of prominent spectral features from the C2-C1 Fourier transform. Vertical axis measured in units of power (mmag^2). Frequency span 0-40 c/d.

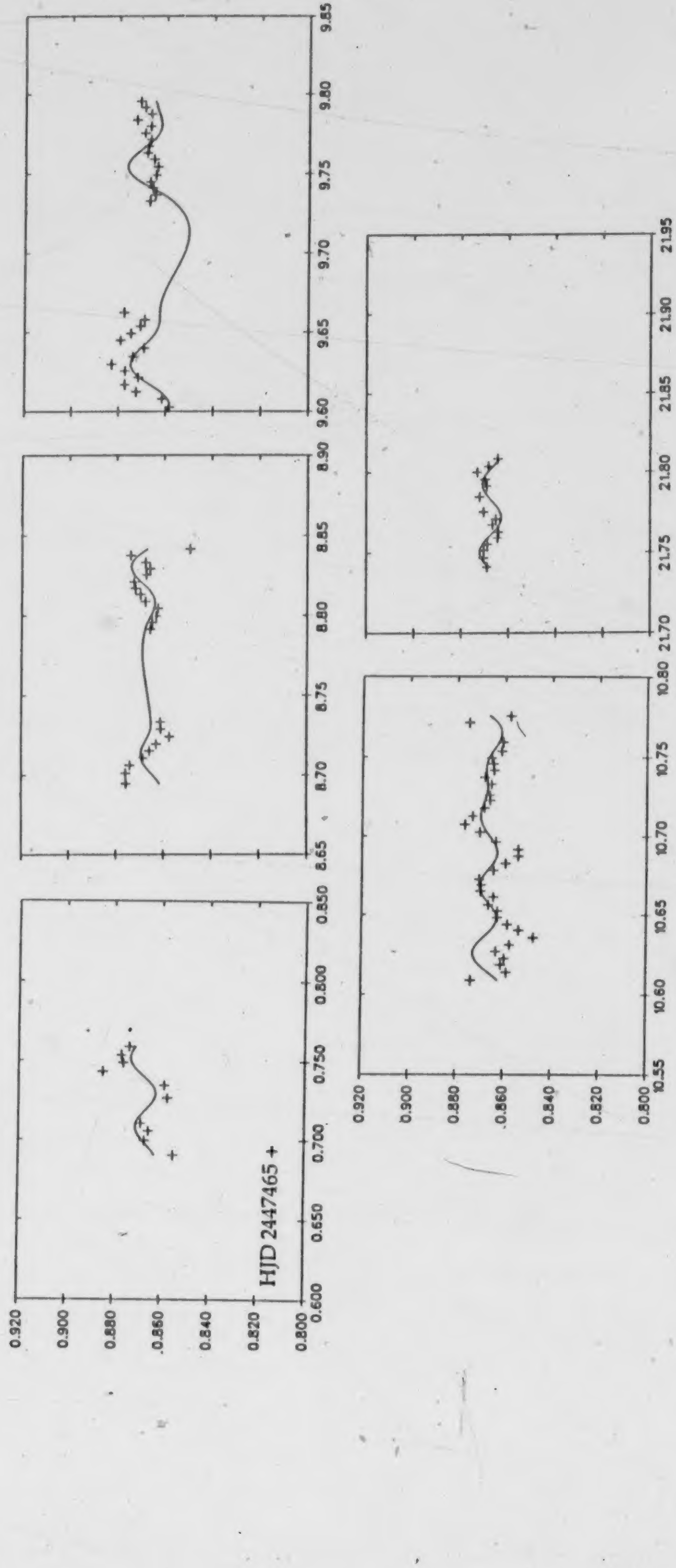


Figure 9.13 Three frequency fit to (V - C1) data for HR 729.

V-C1		V-C2		C2-C1	
Freq. (c/d)	Amp. (mmag)	Freq. (c/d)	Amp. (mmag)	Freq. (c/d)	Amp. (mmag)
17.34	4.3	17.36	4.2	7.24	6.2
14.74	3.7	21.40	4.1	6.08	4.7
6.42	3.5	14.74	3.7	8.48	3.5
23.90	3.2	24.00	3.3		
28.62	3.1				

Possible Consistent Frequencies (averaged):

Frequency (c/d)	Amplitude (mmag)
17.35	4.3
14.74	3.7
24.00	3.3

False alarm level A99% = 4.1 mmag

Table 9.5 Possible frequency solution for HR 729. The final three frequencies given are averages of those frequencies appearing in both V-C1 and V-C2. The 99% confidence level = 4.1 mmag.

9.3.2 The Campaign on KW 207

The δ-Scuti star KW 207 (= HD 73576 = BU Cnc, α(2000) = $8^h39^m44^s$,δ(2000) = 19°16'34") is a low amplitude variable with mean V magnitude = 7.5. The star is a member of the Praesepe cluster and the proximity of cluster standard stars KW 276 (= HD 73711 = C1, F0 II, V = 7.4) and KW 348 (= HD 73819 = C2, A6 V, V = 6.8) helped ensure high photometric accuracy in the measurements. The star is situated on the main sequence and is known to be a fast rotator. Preliminary observations by Breger indicate the possibility of 3 frequencies in the 16 to 20 c/d range. The campaign on KW 207 ran from February 6 - 26, 1989. Seven nights of high quality data were obtained from Devon.

9.3.2.1 Observing Protocol for KW 207

All observations reported were in the Johnson V filter and consisted of sets of 3, 40 second integrations in the sequence C1 - V - C2. Sky corrections were made as necessary. Table 9.6 summarizes the data for the entire campaign. Figures 9.14 - 9.16 show the V filter light curves for V-C1, V-C2, and C2-C1. It is readily apparent from these that the C2-C1 light curves are not constant. This point will be addressed in the next section. The observing journal for the campaign appears in Table 9.7 and it should be noticed that a large zero point correction was needed for the night of February 18, 1989. The full Moon was very close to the Praesepe cluster on this evening and the anomalous zero points are likely due to residual sky brightness. When this correction is applied the zero points are consistent to within a few mmag for the duration of the campaign.

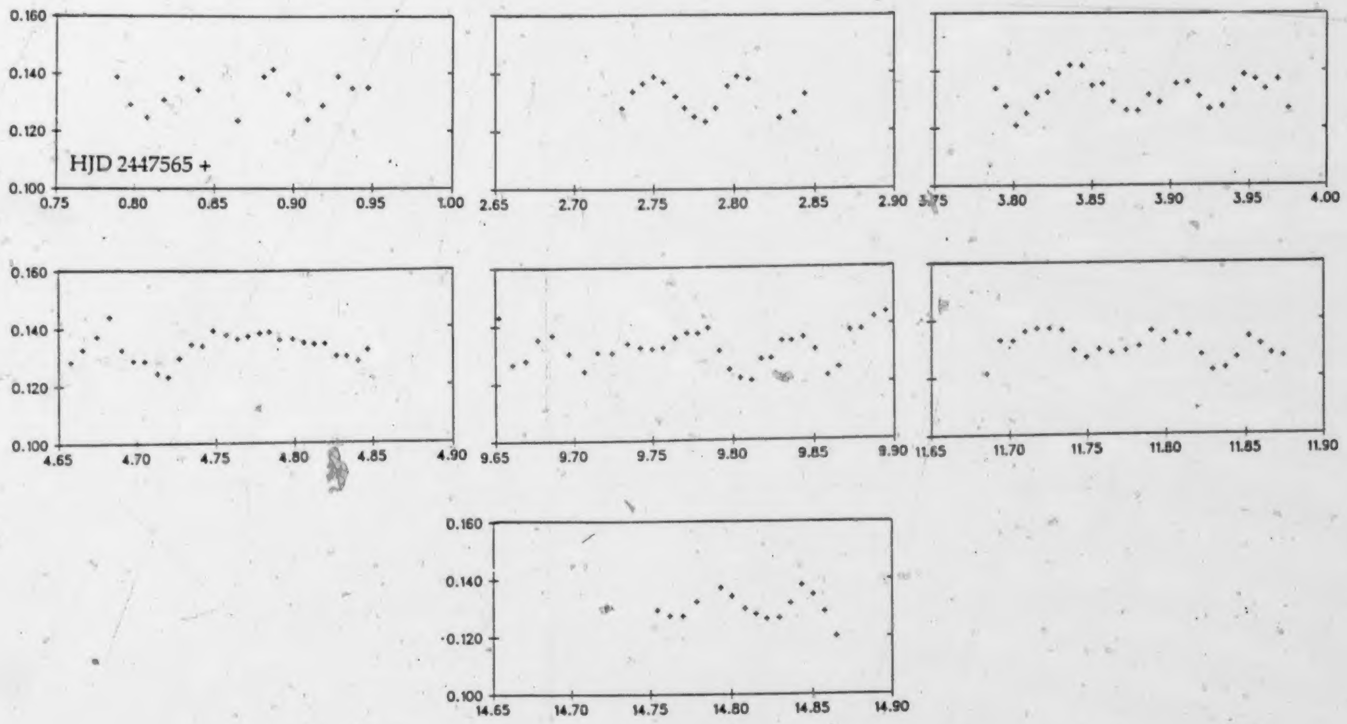


Figure 9.14 KW 207 - KW 276 (V - C1) plots for the February campaign on KW 207. All plots are in the Johson V filter.

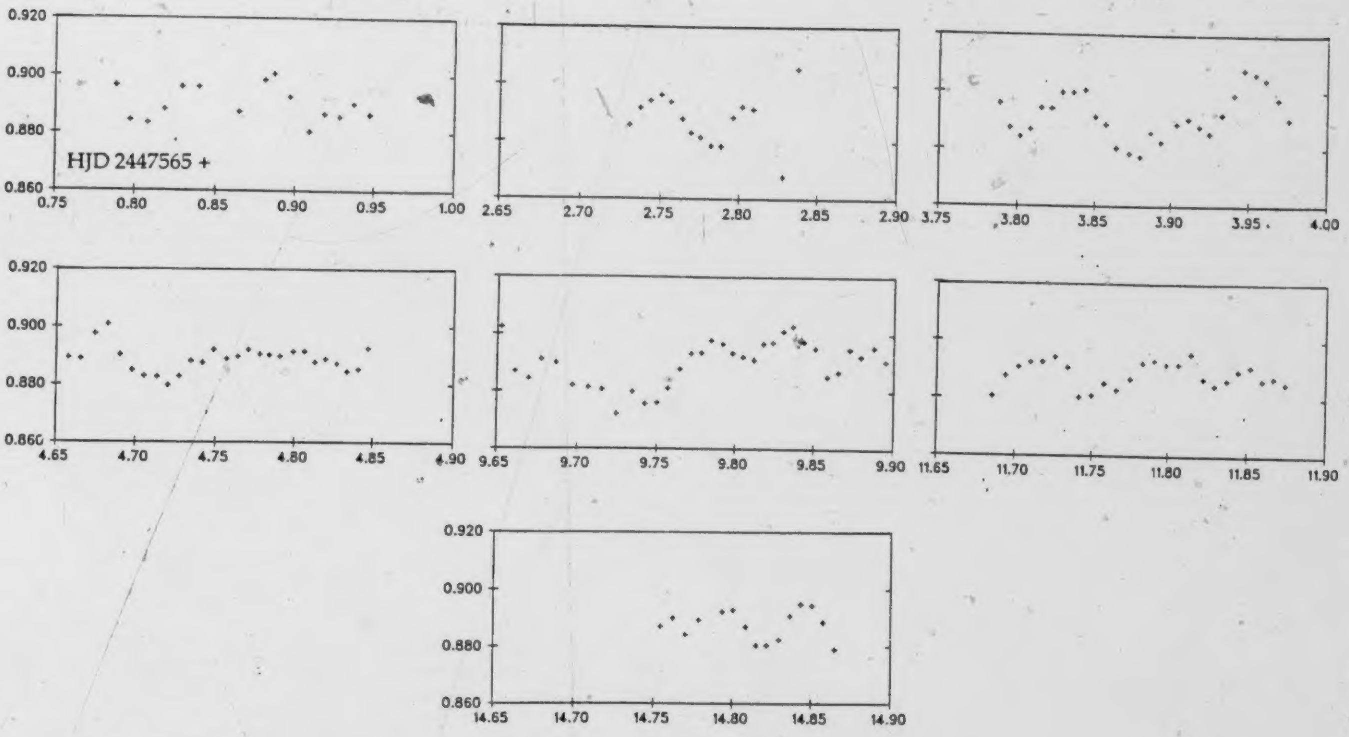


Figure 9.15 KW 207 - KW 348 (V - C2) plots for the February campaign on KW 207. All plots are in the Johson V filter.

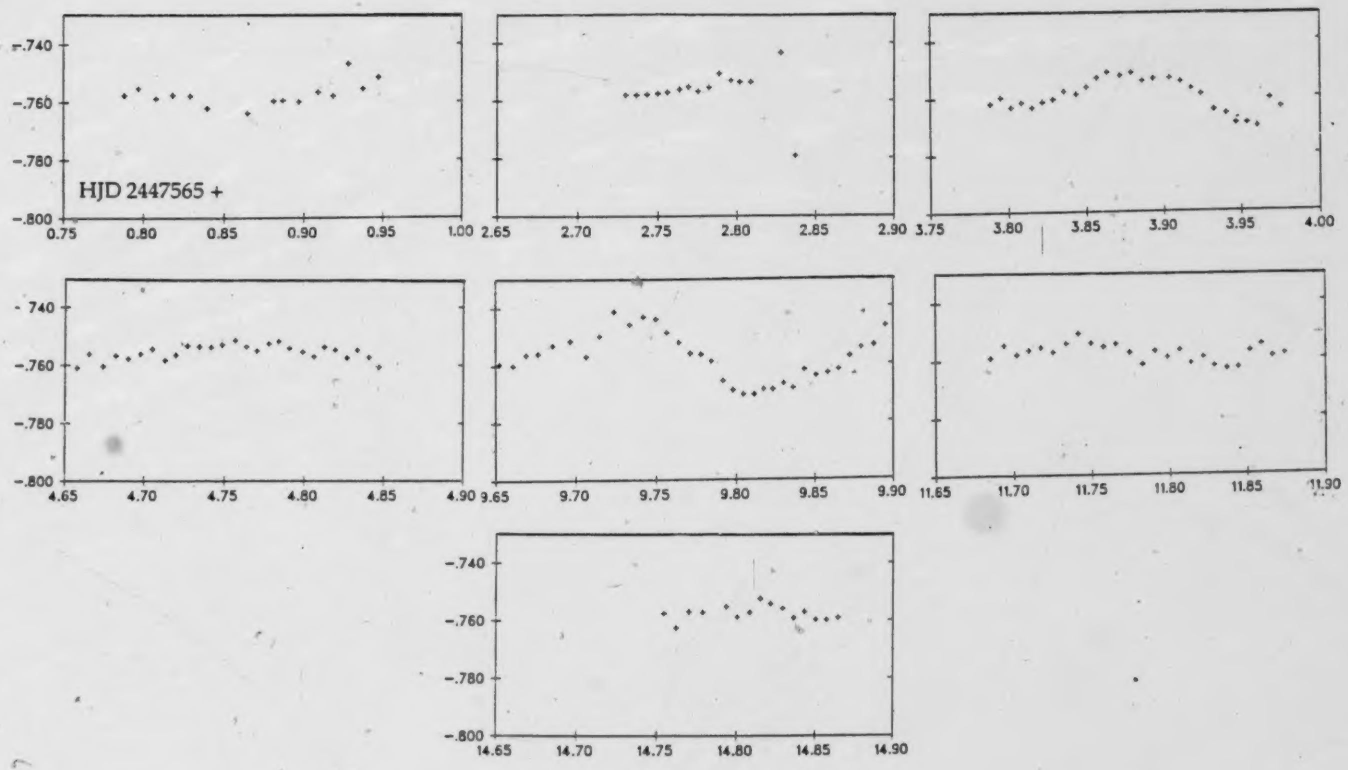


Figure 9.16 KW 348 - KW 276 (C2 - C1) plots for the February campaign on KW 207. All plots are in the Johson V filter.

HJD	V - C1	V - C2	C1 - C2	HJD	V - C1	V - C2	C1 - C2	HJD	V - C1	V - C2	C1 - C2
2447565.7881	0.1388	0.8965	-0.7576	2447568.9682	0.1370	0.8974	-0.7605	2447574.8045	0.1216	0.8921	-0.7704
2447565.7970	0.1292	0.8844	-0.7552	2447568.9751	0.1268	0.8904	-0.7636	2447574.8114	0.1207	0.8911	-0.7705
2447565.8079	0.1247	0.8835	-0.7587	2447569.5974	0.1322	0.8887	-0.7565	2447574.8173	0.1280	0.8967	-0.7687
2447565.8182	0.1307	0.8882	-0.7575	2447569.6060	0.1304	0.8881	-0.7577	2447574.8233	0.1284	0.8972	-0.7688
2447565.8289	0.1384	0.8961	-0.7578	2447569.6138	0.1330	0.8968	-0.7638	2447574.8300	0.1344	0.9011	-0.7667
2447565.8394	0.1342	0.8961	-0.7620	2447569.6220	0.1342	0.8962	-0.7620	2447574.8360	0.1344	0.9028	0.7683
2447565.8644	0.1236	0.8874	-0.7638	2447569.6294	0.1243	0.8937	-0.7694	2447574.8433	0.1355	0.8974	-0.7619
2447565.8808	0.1389	0.8985	-0.7596	2447569.6375	0.1331	0.8762	-0.7431	2447574.8507	0.1313	0.8952	-0.7639
2447565.8866	0.1414	0.9007	-0.7594	2447569.6458	0.1277	0.8712	-0.7435	2447574.8584	0.1223	0.8853	-0.7630
2447565.8965	0.1327	0.8926	-0.7599	2447569.6577	0.1284	0.8893	-0.7609	2447574.8654	0.1251	0.8869	-0.7618
2447565.9088	0.1240	0.8806	-0.7566	2447569.6653	0.1327	0.8889	-0.7562	2447574.8725	0.1377	0.8949	-0.7572
2447565.9181	0.1288	0.8867	-0.7579	2447569.6741	0.1372	0.8976	-0.7604	2447574.8796	0.1381	0.8924	-0.7543
2447565.9277	0.1389	0.8857	-0.7468	2447569.6821	0.1440	0.9008	-0.7568	2447574.8876	0.1423	0.8956	-0.7534
2447565.9370	0.1348	0.8902	-0.7554	2447569.6899	0.1325	0.8903	-0.7578	2447574.8950	0.1440	0.8907	-0.7468
2447565.9471	0.1351	0.8866	-0.7515	2447569.6977	0.1287	0.8849	-0.7561	2447576.6852	0.1334	0.9052	-0.7717
2447567.7301	0.1279	0.8857	-0.7579	2447569.7052	0.1285	0.8829	-0.7544	2447576.6937	0.1450	0.9123	-0.7673
2447567.7368	0.1337	0.8917	-0.7579	2447569.7132	0.1243	0.8826	-0.7583	2447576.7019	0.1448	0.9154	-0.7706
2447567.7431	0.1365	0.8942	-0.7577	2447569.7199	0.1231	0.8797	-0.7565	2447576.7096	0.1480	0.9171	-0.7691
2447567.7498	0.1388	0.8962	-0.7574	2447569.7269	0.1296	0.8828	-0.7533	2447576.7174	0.1490	0.9172	-0.7682
2447567.7557	0.1368	0.8938	-0.7570	2447569.7343	0.1344	0.8880	-0.7536	2447576.7253	0.1490	0.9189	-0.7698
2447567.7632	0.1319	0.8879	-0.7560	2447569.7414	0.1338	0.8875	-0.7538	2447576.7336	0.1485	0.9153	-0.7668
2447567.7688	0.1280	0.8831	-0.7551	2447569.7483	0.1391	0.8921	-0.7529	2447576.7413	0.1415	0.9049	-0.7634
2447567.7749	0.1250	0.8815	-0.7566	2447569.7564	0.1376	0.8889	-0.7514	2447576.7493	0.1389	0.9056	-0.7667
2447567.7818	0.1233	0.8786	-0.7553	2447569.7635	0.1361	0.8897	-0.7536	2447576.7572	0.1417	0.9098	-0.7680
2447567.7883	0.1279	0.8784	-0.7505	2447569.7701	0.1370	0.8920	-0.7550	2447576.7651	0.1405	0.9075	-0.7670
2447567.7958	0.1355	0.8885	-0.7529	2447569.7775	0.1380	0.8905	-0.7526	2447576.7740	0.1413	0.9114	-0.7701
2447567.8016	0.1389	0.8923	-0.7534	2447569.7836	0.1384	0.8902	-0.7518	2447576.7823	0.1427	0.9169	-0.7742
2447567.8086	0.1379	0.8914	-0.7535	2447569.7903	0.1357	0.8898	-0.7541	2447576.7902	0.1481	0.9178	-0.7696
2447567.8276	0.1245	0.8678	-0.7433	2447569.7988	0.1359	0.8914	-0.7554	2447576.7982	0.1445	0.9164	-0.7718
2447567.8370	0.1264	0.9056	-0.7792	2447569.8058	0.1346	0.8916	-0.7570	2447576.8063	0.1472	0.9165	-0.7693
2447567.8436	0.1327	0.7659	-0.6331	2447569.8123	0.1341	0.8878	-0.7537	2447576.8140	0.1464	0.9202	-0.7738
2447568.7882	0.1339	0.8959	-0.7620	2447569.8191	0.1342	0.8889	-0.7547	2447576.8220	0.1397	0.9115	-0.7718
2447568.7948	0.1277	0.8874	-0.7598	2447569.8264	0.1299	0.8873	-0.7574	2447576.8291	0.1343	0.9092	-0.7749
2447568.8014	0.1210	0.8843	-0.7633	2447569.8330	0.1298	0.8846	-0.7548	2447576.8369	0.1352	0.9110	-0.7758
2447568.8080	0.1252	0.8868	-0.7616	2447569.8404	0.1282	0.8854	-0.7572	2447576.8441	0.1387	0.9142	-0.7754
2447568.8149	0.1310	0.8943	-0.7634	2447569.8466	0.1320	0.8927	-0.7606	2447576.8517	0.1460	0.9157	-0.7697
2447568.8216	0.1326	0.8941	-0.7615	2447574.6410	0.1414	0.8999	-0.7585	2447576.8590	0.1434	0.9110	-0.7675
2447568.8284	0.1391	0.8997	-0.7605	2447574.6523	0.1431	0.9024	-0.7593	2447576.8662	0.1401	0.9119	-0.7717
2447568.8355	0.1420	0.8997	-0.7577	2447574.6609	0.1268	0.8869	-0.7601	2447576.8738	0.1391	0.9099	-0.7708
2447568.8433	0.1418	0.9006	-0.7588	2447574.6693	0.1280	0.8843	-0.7563	2447579.7541	0.1293	0.8870	-0.7576
2447568.8498	0.1349	0.8912	-0.7563	2447574.6768	0.1353	0.8911	-0.7559	2447579.7618	0.1273	0.8899	-0.7626
2447568.8564	0.1355	0.8886	-0.7531	2447574.6858	0.1368	0.8899	-0.7531	2447579.7698	0.1272	0.8842	-0.7570
2447568.8630	0.1293	0.8804	-0.7511	2447574.6966	0.1304	0.8820	-0.7516	2447579.7783	0.1322	0.8893	-0.7572
2447568.8714	0.1262	0.8785	-0.7523	2447574.7066	0.1243	0.8813	-0.7570	2447579.7933	0.1370	0.8922	-0.7552
2447568.8786	0.1260	0.8773	-0.7513	2447574.7151	0.1307	0.8806	-0.7499	2447579.8002	0.1341	0.8929	-0.7588
2447568.8858	0.1316	0.8858	-0.7542	2447574.7244	0.1305	0.8720	-0.7415	2447579.8082	0.1298	0.8870	-0.7572
2447568.8928	0.1290	0.8824	-0.7534	2447574.7341	0.1337	0.8798	-0.7460	2447579.8149	0.1279	0.8804	-0.7525
2447568.9035	0.1354	0.8887	-0.7533	2447574.7422	0.1323	0.8756	-0.7433	2447579.8214	0.1263	0.8805	-0.7542
2447568.9108	0.1361	0.8905	-0.7545	2447574.7498	0.1318	0.8760	-0.7441	2447579.8291	0.1266	0.8824	-0.7558
2447568.9180	0.1310	0.8879	-0.7569	2447574.7565	0.1323	0.8811	-0.7488	2447579.8361	0.1317	0.8908	-0.7591
2447568.9245	0.1266	0.8855	-0.7589	2447574.7639	0.1356	0.8878	-0.7522	2447579.8430	0.1380	0.8949	-0.7570
2447568.9326	0.1275	0.8921	-0.7645	2447574.7711	0.1372	0.8932	-0.7560	2447579.8502	0.1347	0.8944	-0.7597
2447568.9403	0.1332	0.8990	-0.7658	2447574.7778	0.1371	0.8935	-0.7564	2447579.8573	0.1288	0.8886	-0.7598
2447568.9466	0.1386	0.9078	-0.7692	2447574.7842	0.1389	0.8978	-0.7588	2447579.8647	0.1202	0.8791	-0.7590
2447568.9538	0.1371	0.9063	-0.7692	2447574.7915	0.1310	0.8966	-0.7657				
2447568.9602	0.1337	0.9042	-0.7704	2447574.7978	0.1245	0.8934	-0.7689				

Table 9.6 Summary of data for the δ-Scuti variable KW 207 and the comparison stars KW 276 (C1) and KW 348 (C2). All observations are in the Johnson V filter.

Journal of Observations
KW 207 February 7 - 21, 1989

Date	V - C1 V Mag	σ V Mag	V - C2 V Mag	σ V Mag	C1 - C2 V Mag	σ V Mag
Feb 7	0.1329	0.0057	0.8903	0.0059	-0.7573	0.0040
Feb 9	0.1315	0.0055	0.8878	0.0088	-0.7562	0.0071
Feb 10	0.1319	0.0060	0.8896	0.0074	-0.7578	0.0043
Feb 11	0.1314	0.0048	0.8885	0.0078	-0.7571	0.0065
Feb 16	0.1329	0.0049	0.8847	0.0082	-0.7518	0.0059
Feb 21	0.1301	0.0045	0.8876	0.0050	-0.7575	0.0024
Feb 18*	0.1438	0.0043	0.9128	0.0049	-0.7690	0.0025

zero point corrections to Feb 18	0.0120	0.0247	-0.0126

zero point average

V Mag	0.1315	0.8878	-0.7562
σ	0.0055	0.0088	0.0071

total number of observations N_0 = 166

Table 9.7 Journal of observations for the February campaign on KW 207.

9.3.2.2 Frequency Analysis for KW 207 and the Anomalous Behaviour of C2

The methods discussed for HR 729 were applied to KW 207 as well and will not be repeated here. Figure 9.17 shows a scan of 1000 frequencies in the range 2 - 100 c/d for the V-C1 data set. The vertical axis is in units of power (mmag^2) with the 99% confidence level as shown. It is apparent from this scan that power is concentrated in the 16 - 20 c/d range. Figures 9.18 - 9.20 show the power spectra for the data sets V-C1, V-C2 and C2-C1 in the range 2 - 22 c/d as well as the spectral window for the data sets. A comparison of these transforms is quite revealing. Both the V-C1 and V-C2 transforms show similar structure in the 16 - 20 c/d range. V-C2, however, shows considerable power concentrated around 6 c/d. This structure is absent in the V-C1 transform but is again strong - and in fact the only significant feature - in the C2-C1 transform. A consistent spectral feature in both V-C2 and C2-C1 is found at a frequency of 5.80 c/d. This observation is consistent with the obvious variability in the C2-C1 data set shown in Figure 9.16. The suggestion is put forward that C2 (HD 73819) is in fact a low amplitude variable star with a dominant period 4.14^h and amplitude 4.8 mmag and should not be used as a comparison star in the future(16). The modulations in the C2-C1 light curve suggest that C2 may be a multimode pulsator and the C2-C1 Fourier transform shown in Figure 9.21 suggests that more than one frequency may be present but the data are too limited to permit further comment on this.

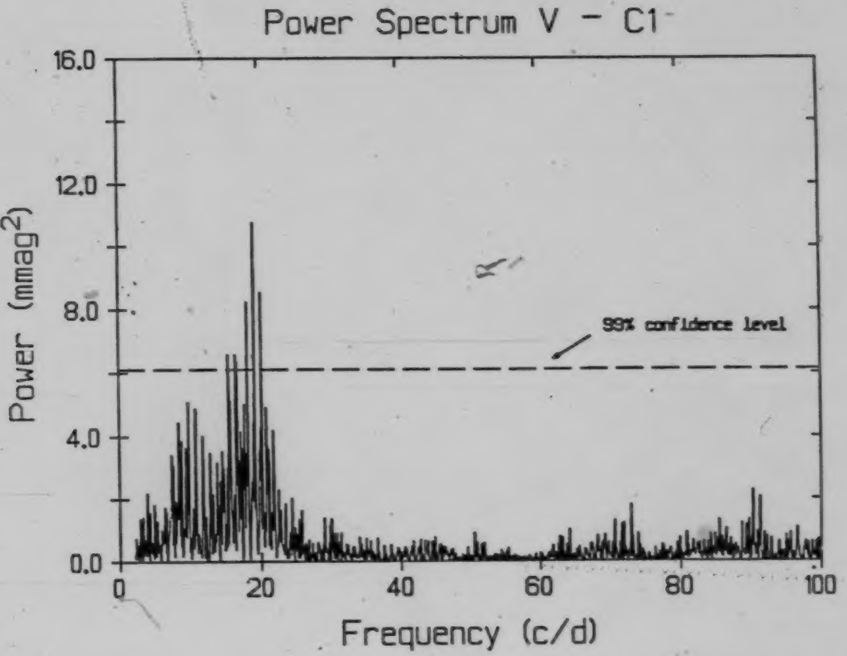


Figure 9.17 Power spectrum for the data set V-C1 consisting of 1000 scans in the range 2 - 100 c/d. False alarm level is at 6.9 mmag^2.

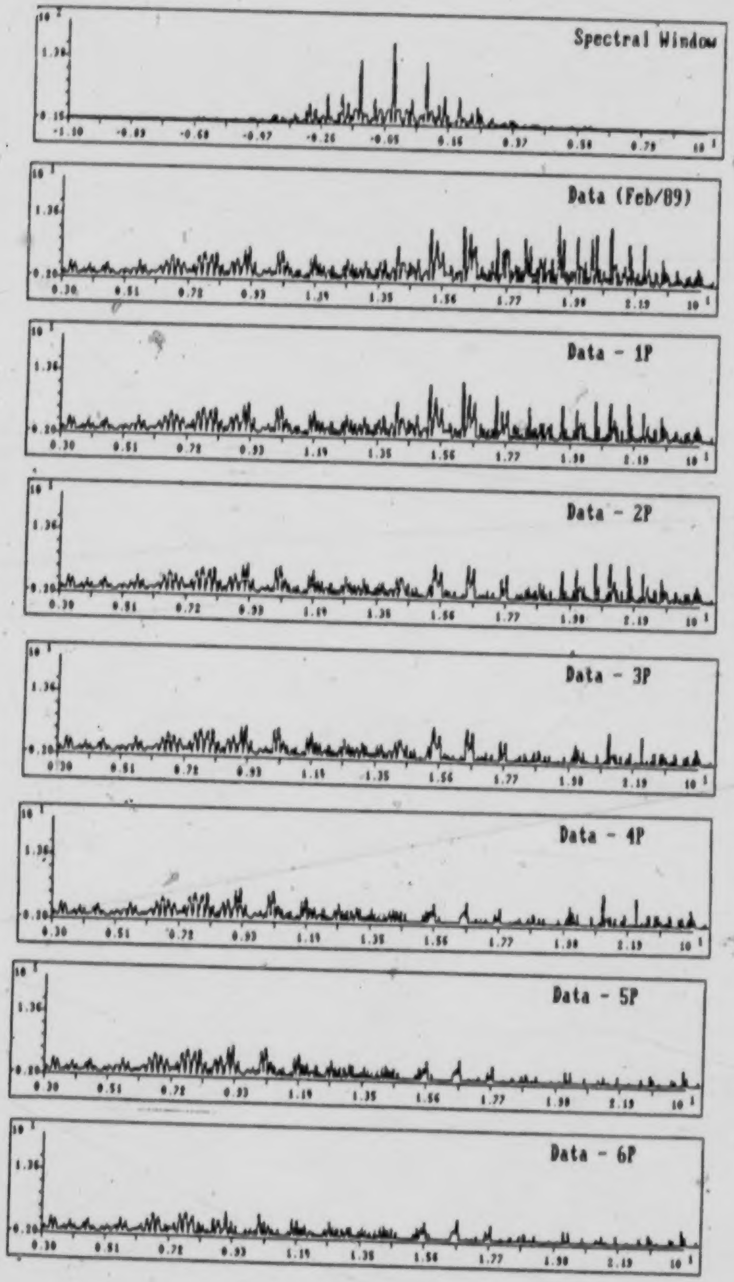


Figure 9.18 Spectral window and removal of prominent spectral features from the V-C1 Fourier transform. Vertical axis measured in units of power (mmag^2). Frequency span 2-22 c/d.

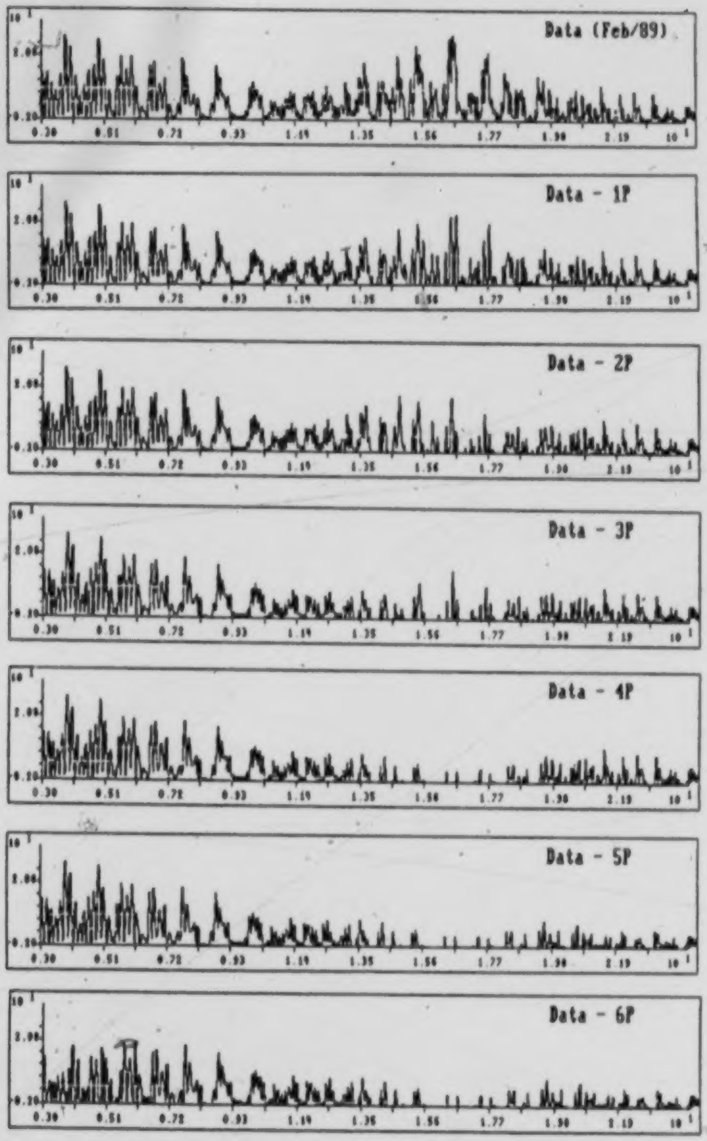


Figure 9.19 Spectral window and removal of prominent spectral features from the V-C2 Fourier transform. Vertical axis measured in units of power (mmag^2). Frequency span 2-22 c/d.

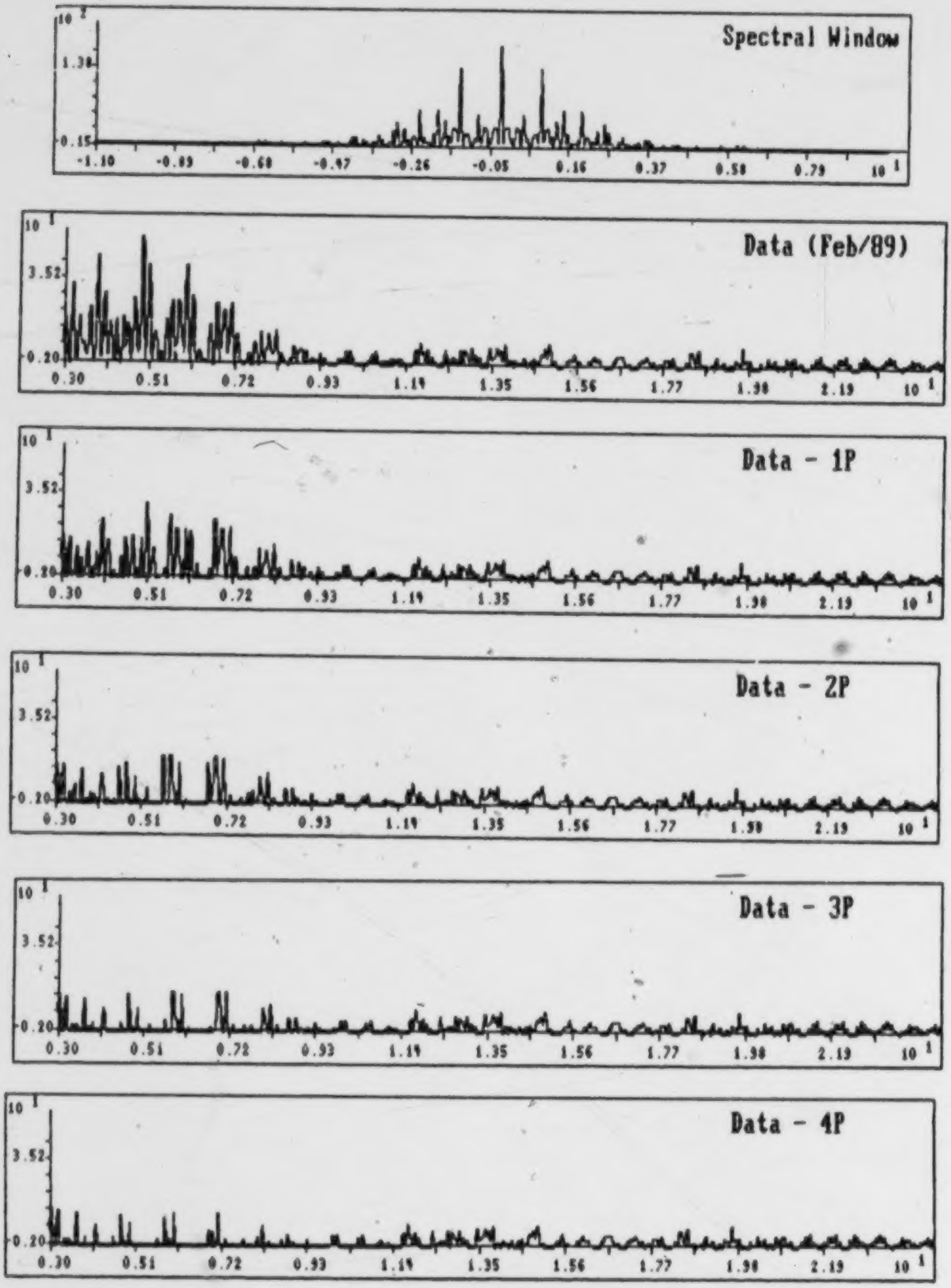


Figure 9.20 Spectral window and removal of prominent spectral features from the C2-C1 Fourier transform. Vertical axis measured in units of power (mmag^2). Frequency span 2-22 c/d.

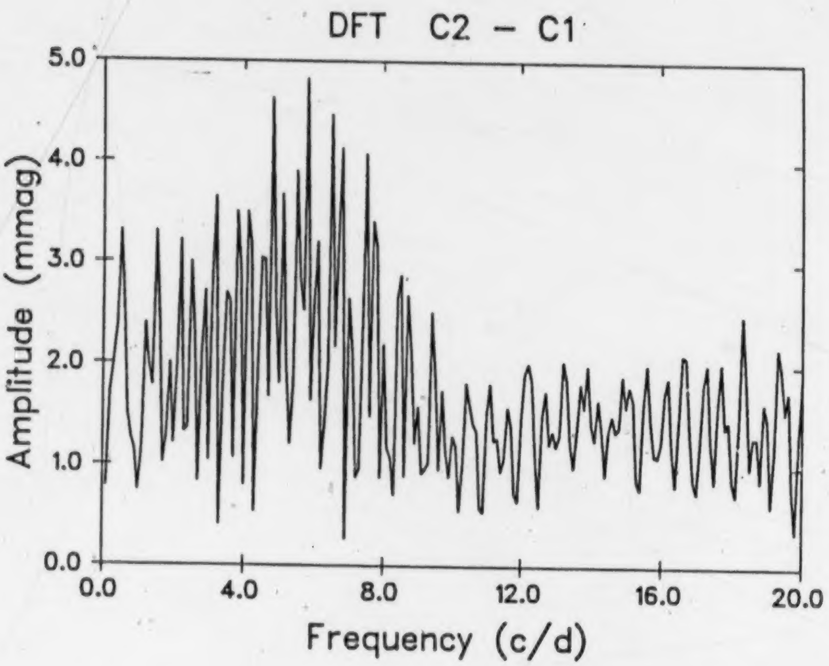


Figure 9.21 Spectral scan for C2-C1 in the 0-20 c/d range.

The frequency spectra for both the V-C1 and V-C2 sets are very rich. Figure 9.22 shows these sets in the range 12-22 c/d. Despite the heavily aliased patterns, seven consistent frequencies can be identified in both scans. These frequencies appear in Table 9.8. This confirms the earlier suggestion by Breger that KW 207 pulsates with at least 3 frequencies in the 16 - 20 c/d range. The 99% confidence level is based on that of the V-C1 scans. From this set of possible frequencies a cosine fit to the data in the time domain was attempted. When such a fit was constructed it was found that not all of the frequencies given in table 9.8 lead to satisfactory results. Figure 9.23 shows the result of fitting 4 of the 7 frequency-amplitude pairs given in Table 9.8. Overall the fit to the data is good, lending credibility to the frequency solution suggested here. Figure 9.24 shows the residuals (Observed - Calculated) for the cosine fit. The Fourier tranform of the residual data is shown in Figure 9.25 and displays no significant spectral features in the frequency range 6 - 22 c/d. The suggested preliminary frequency-amplitude solution for KW 207 is given in Table 9.9.

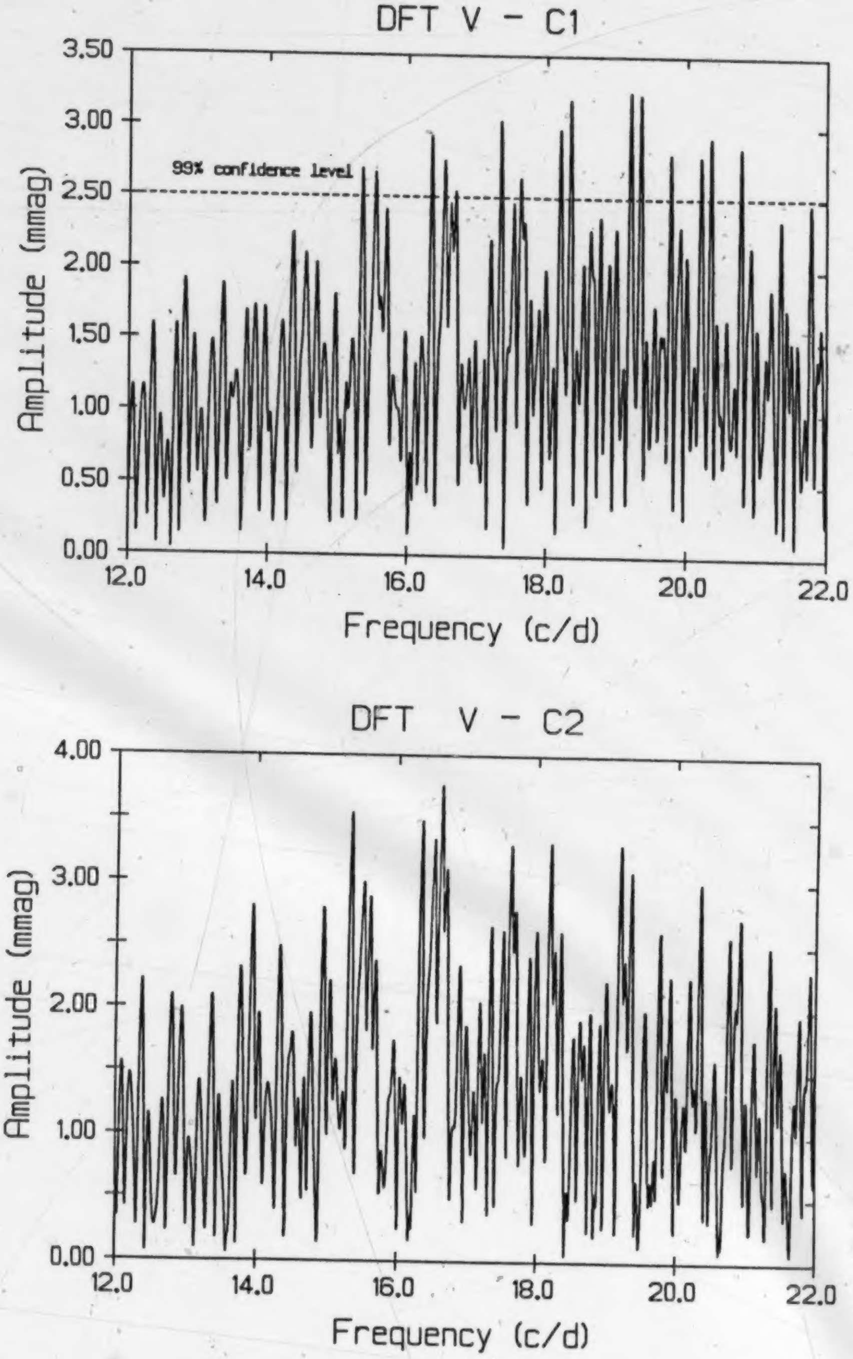


Figure 9.22 Spectral scans (without window removal) for V-C1 and V-C2 in the frequency range 16-20 c/d. Seven frequency matches above the 99% confidence level for V-C1 are found for both scans.

V-C1		V-C2		C2-C1	
Freq. (c/d)	Amp. (mmag)	Freq. (c/d)	Amp. (mmag)	Freq. (c/d)	Amp. (mmag)
16.34	3.1	16.34	3.5	5.80	4.8
16.53	2.7	16.52	3.3	6.50	4.5
16.63	2.5	16.62	3.8		
16.72	2.6	16.70	3.1		
19.20	3.3	19.19	3.3		
19.34	3.2	19.35	3.1		
20.77	2.9	20.77	2.6		
		5.80	4.4		

Possible Consistent Frequencies (averaged):

V - C1

Frequency (c/d)	Amplitude (mmag)
16.34	3.3
16.53	3.0
16.63	3.1
16.71	2.9
19.20	3.3
19.35	3.2
20.77	2.8

False alarm level $A_{99\%} = 2.5$ mmag for V - C1

C2 - C1

Frequency (c/d)	Amplitude (mmag)
5.80	4.8

False alarm level $A_{99\%} = 4.1$ mmag for C2 - C1

Table 9.8 Possible frequency solution for KW 207. The final seven frequencies given are averages of those frequencies appearing in both V-C1 and V-C2. The frequency given for C2 - C1 is the sole match between the C2 - C1 and V - C2 sets.

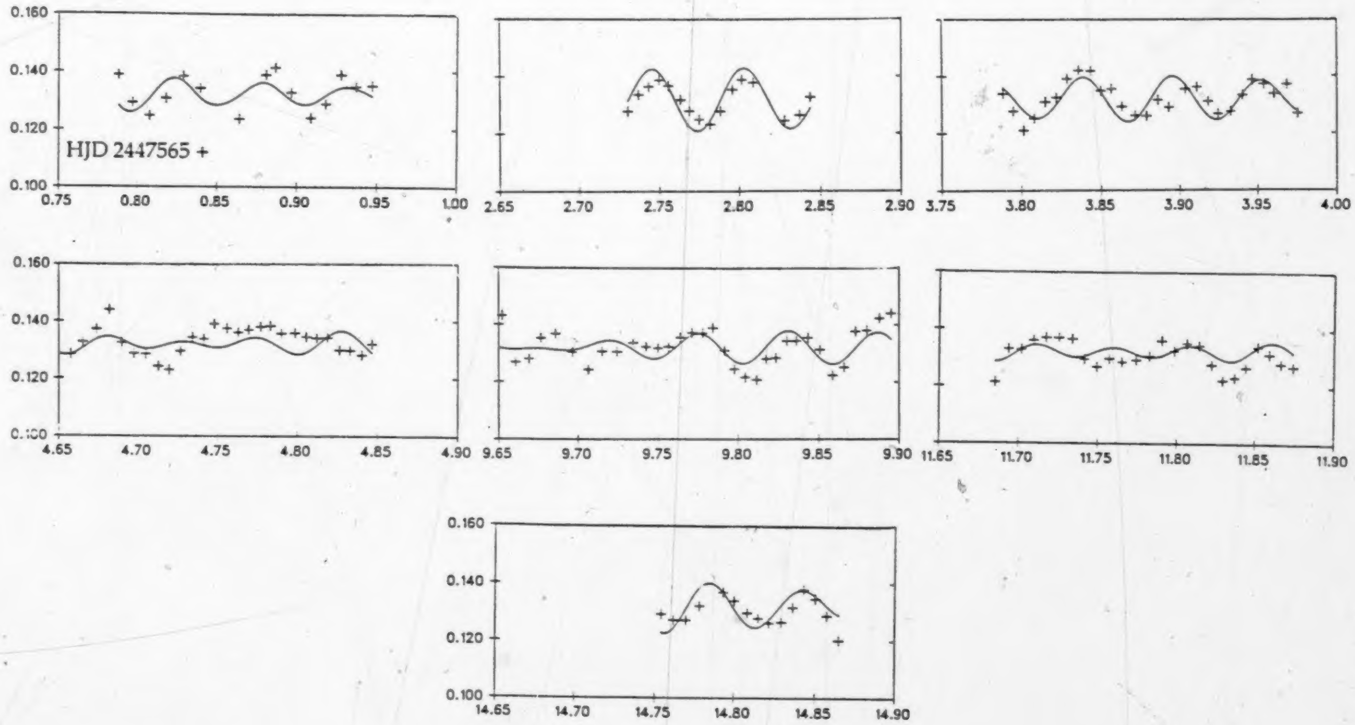


Figure 9.23 Four frequency fit to the data (V-C1) for KW 207.

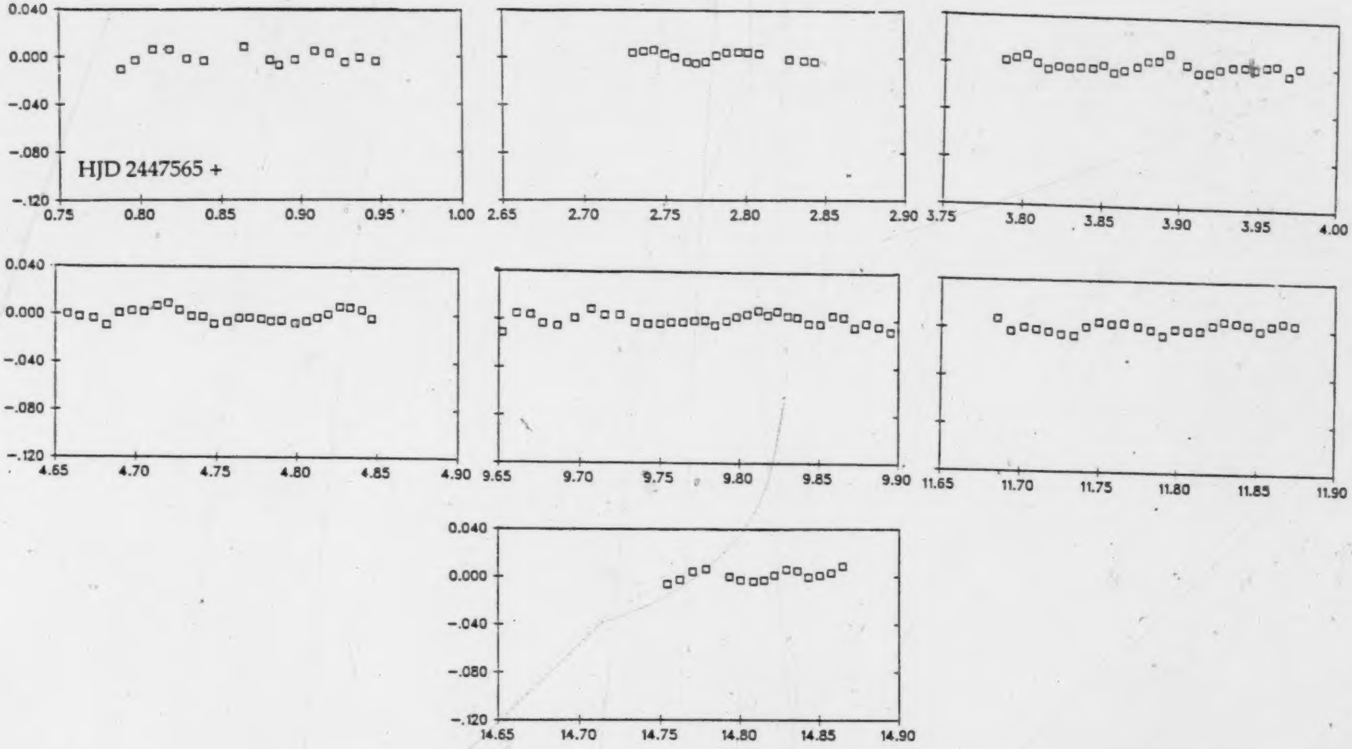


Figure 9.24 The residuals (observed-calculated) for the four frequency fit to the data for KW 207 shown in Figure 9.23

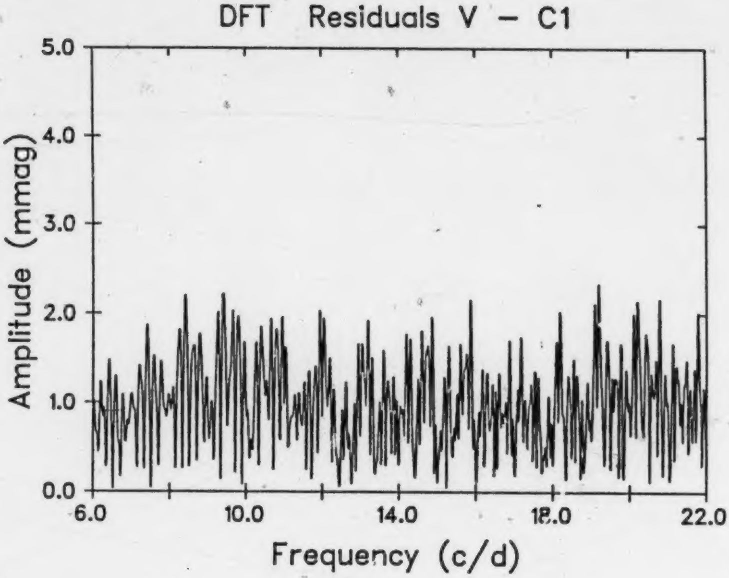


Figure 9.25 The Fourier transform of the residuals of the 4 frequency fit to the KW 207 data. No significant spectral features appear throughout the 6 - 22 c/d interval.

Frequency (c/d)	Amplitude (mmag)
19.20	3.3
16.34	3.1
16.53	2.8
16.70	2.6

Table 9.9 Provisional frequency-amplitude solution for KW 207 based on data collected at the Devon Astronomical Observatory during the February 1989 international campaign on the δ -Scuti star KW 207.

9.4 Interpretation of the Frequency Analysis for HR 729 and KW 207

Before any suggestion is made concerning the nature of the frequencies of oscillation found for HR 729 and KW 207 a brief overview of the theory of stellar pulsation will be given.

9.4.1 Stellar Pulsation - an Overview

The simplest possible mode of oscillation for a variable star is the fundamental inward-outward or radial mode. The majority of pulsating stars appear to oscillate in this mode and obey the well known period-density relationship:

$$\Pi(\bar{\rho})^{1/2} \cong \mathit{constant} \qquad 9.11$$

where Π is the pulsation period and ρ is the mean density of the star. Equation 9.11 suggests that the period of a large tenuous star is greater than that of a more compact one. This conforms to a simple intuitive notion that stellar pulsation periods should be approximately equal to the time required for a sound wave to traverse the mean stellar diameter.

A simple derivation of the period-density law can be obtained by imagining that a star consists of a thin shell of mass M and radius R enclosing a pressurized gas of negligible mass. The shell will be stable if the inward force of gravity is balanced by the outward pressure exerted on the shell. The gravitational force is given by the expression

$$\mathcal{F}_{\text{Gravity}} = \frac{GM}{R^2}\rho \qquad 9.12$$

and the pressure support force is

$$\mathcal{F}_{\text{Press.}} = \frac{P}{R} \qquad 9.13$$

When the star is in balance the following condition holds:

$$\mathcal{F}_{\text{Gravity}} - \mathcal{F}_{\text{Press.}} = 0 \tag{9.14}$$

Now imagine a small perturbation on the shell away from equilibrium. This will result in a small change to the density, pressure and radius. The equilibrium between gravity and buoyant forces will be upset. If the variation in F_{gravity} and F_{pressure} per unit mass is calculated, the difference between them (by Newton's second law) equals the acceleration of the thin shell toward or away from its equilibrium position. Using the technique of linearization it is easy to relate the variation in density to the variation in the radius. If the gas is assumed,to behave adiabatically then the following condition holds

$$\frac{\delta P}{P} = \gamma \frac{\delta \rho}{\rho} \tag{9.15}$$

and the local pressure variation can be written

$$\delta P = -3\gamma P \delta R/R \qquad \delta\rho = -3\rho\delta R/R \tag{9.16}$$

The gravity and pressure support variations then become

$$\delta\left(\frac{\mathcal{F}_{\text{Gravity}}}{\rho}\right) = \frac{4\pi G}{3}(\rho\delta R + R\delta\rho) \tag{9.17}$$

$$\delta\left(\frac{\mathcal{F}_{\text{Press.}}}{\rho}\right) = \frac{\delta P}{R\rho} - \frac{P\delta R}{\rho R^2} - \frac{P\delta\rho}{\rho^2 R} \tag{9.18}$$

From this the second time derivative of the radius variation can be written as

$$\delta\ddot{R} = \frac{4\pi G}{3}(\rho\delta R+R\delta\rho) - \frac{\delta P}{R\rho} + \frac{P\delta R}{\rho R^2} + \frac{P\delta\rho}{\rho^2 R} \qquad 9.19$$

This can be easily rearranged to give the familiar equation for simple harmonic motion and results in the period-density law

$$\delta\ddot{R} = (3\gamma\text{-}4)\frac{4\pi G}{3}\rho\delta R \qquad 9.20$$

$$\Pi = \frac{2\pi}{[(3\gamma\text{-}4)\cdot 4/3\ \pi G\rho]^{1/2}} \qquad 9.21$$

While the model presented here is highly simplistic it does recover the correct expression for the fundamental mode of a constant density star and provides useful insight into the nature of stellar pulsation.(17)

In addition to the fundamental radial mode, there is, in principle, an infinite spectrum of radial overtones (analogous to the overtones in a musical instrument) that could be present in a star. Both the δ-Scuti and beat Cepheid stars provide examples of pulsation at two or more frequencies that can be identified with radial overtones.

Equation 9.21 is usually written in the form

$$\Pi(\rho/\rho_{\odot}) = Q \qquad 9.22$$

where Q is known as the **pulsation constant** and is a quantity which depends on both the structure of the star as well as the particular radial overtone. Table 9.10 lists Q values derived by Stellingwerf(18) for a "typical" δ-Scuti star. The importance of such a tabulation lies in the identification of observed frequencies with specific radial overtones. Of particular interest in Table 9.10 is the last column in which ratios of successive overtone periods are listed.

Characteristic Pulsational Q Values for δ-Scuti Variables

Pulsation Mode	Q (days)	P_j/P_{j-1}
Fundamental	0.03259	
1st Overtone	0.02514	0.772
2nd Overtone	0.02050	0.815
3rd Overtone	0.01719	0.838
4th Overtone	0.01470	0.856
5th Overtone	0.01283	0.872

Table 9.10 Table of typical Q values for a δ-Scuti variable $M = 2\ M_\odot$, $\log T_{eff} = 3.88$, $M_{bol} = 1.207$. Adapted from Stellingwerf (1979).

If two frequencies identified in a δ-Scuti light curve are found to form one of these ratios it is compelling evidence that those frequencies can be associated with radial modes of oscillation. A useful relationship for Q(19) in terms of observational parameters is

$$\log Q = -6.454 + \log P + 0.5\log g + 0.1M_{bol} + \log T_{eff} \qquad 9.23$$

where P is the period in days, g is the surface gravity, M_{bol} is the bolometric magnitude and T_{eff} is the effective surface temperature.

While many δ-Scuti stars do display multiple frequencies consistent with successive radial overtones, a significant number of stars pulsate with periods for which no "reasonable"(20) period ratios can be found. These stars provide evidence for the presence of **nonradial** modes of oscillation. Now, in addition to radial modes, the star is able to oscillate in **polar** and **azimuthal** modes running parallel with, and perpendicular to, the stellar equator, respectively. When these additional modes are accounted for the normal modes of oscillation can be written as

$$\tilde{\xi}_{nlm}(r,\theta,\phi,t) = A_n(r)Y^m{}_l(\theta,\phi)e^{-2\pi\nu t} \qquad 9.24$$

where $A_n(r)$ represents the radial mode of oscillation and $Y^m{}_l(,)$ is the spherical harmonic for l = 0,1,2, and m = 0, 1,2, , l.

To understand the significance of the parameters l and m it is first necessary to consider the physical nature of nonradial oscillations in a star. For an oscillation to exist in any medium there must be a restoring mechanism forcing the medium back towards equilibrium. In a star there are two major restoring forces - pressure and buoyancy. In the case of nonradial oscillations it is pressure that supplies the needed restoring force. Such pressure waves are equivalent to sound waves and it is correct to associate nonradial oscillations with the propagation of accoustic waves within the outer layers of a star. Figure 9.26 depicts acoustic waves reflecting in a resonant cavity beneath the stellar surface.

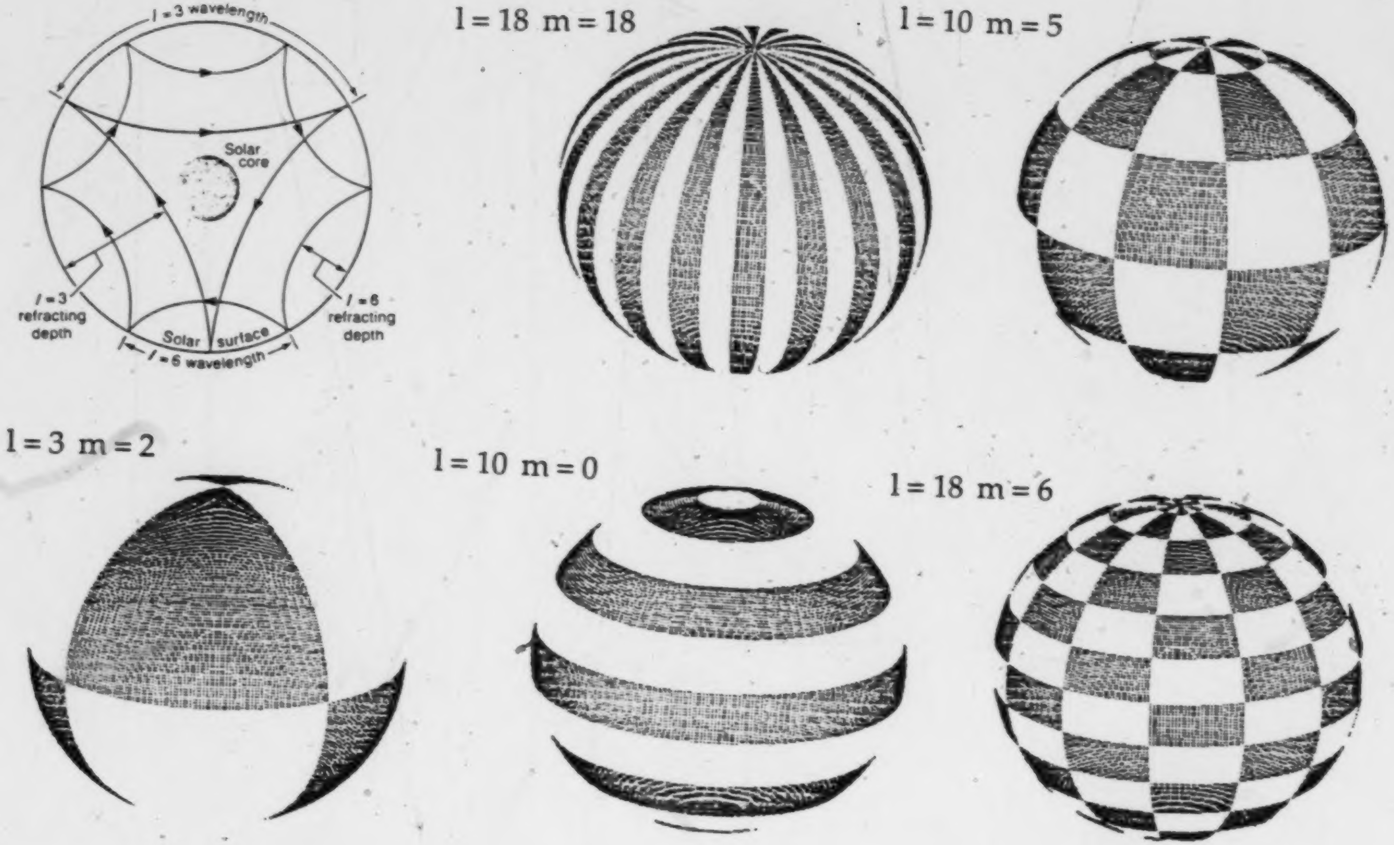

l = 3 wavelength
Solar core
l = 3 refracting depth
l = 6 refracting depth
Solar surface
l = 6 wavelength
l = 18 m = 18
l = 10 m = 5
l = 3 m = 2
l = 10 m = 0
l = 18 m = 6

Figure 9.26 Nonradial oscillations for different values of l and m. Dark areas represent patches on the stellar surface moving inward, light areas are patches moving outward.

The parameter l indicates the number of nodes formed on the stellar surface by the wavefront as it reflects back into the stellar interior. In the absence of stellar rotation (or strong magnetic fields or any other symmetry destroying effect) the nodal lines will form lines of latitude on the stellar surface. The parameter l also determines the depth of penetration of the accoustic waves, where larger values of l indicate oscillations confined to the outer layers of the star. Just as in the case of radial oscillation, there is an infinite spectrum of possible wavelengths and frequencies for waves of a given degree l. These are denoted as **p-modes.**

The spherical harmonic $Y^{m}{}_{l}$ possesses a second parameter m that can, in general, assume (2l+1) values. For nonradial stellar pulsation in spherically symmetric stars the m values are degenerate and do not appear. This symmetry is lifted in the presence of rotation and leads to a splitting of the p-modes. Thus, an l=1 p-mode frequency will split into 3 closely spaced frequencies, an l=2 p-mode will split into 5 frequencies, etc. When such p-mode splitting occurs the frequency spectrum can become extremely complex. Figure 9.26 shows several examples of different l and m combinations. It is this proliferation of possible frequencies of oscillation that provides a rationale for the peculiar frequency ratios observed for some δ-Scuti stars.

Figure 9.27 is a schematic representation of the rich frequency spectrum present when nonradial pulsation occurs. The actual values for the frequencies of these assorted modes have been calculated$^{(21)}$ and depend on the stellar models one employs. The problem facing the observer of δ-Scuti stars is to match the empirically determined frequencies with those computed from detailed stellar models. When both radial and nonradial modes as well as rotational splitting effects are considered the range of possible choices becomes immense and the challenge facing the observer is to find the "correct" match between observation and theory.

9.4.2 Frequency Identification for HR 729 and KW 207

The starting point for any attempted identification of frequencies is the calculation of the pulsation constants Q_i associated with each measured period of oscillation. This has been done and the results are given in Table 9.11. It is instructive to compare these values with those given in Table 9.10. The mean uncertainties in the Q values for both HR 729 and KW 207 were calculated to be 0.003 days and arise primarily from uncertainties in the values adopted for surface gravity and effective temperature for these stars. These uncertainties are comparable to those quoted by Breger et al in their work on 4 CVn(22).

Figure 9.28 shows the pulsational Q values for HR 729 and KW 207 plotted against the Q values taken from tables prepared by Fitch(23). These tables provide Q values for the radial ($l = 0$), $l = 1$, $l = 2$, and $l = 3$ modes for a series of stellar models representing the δ-Scuti variables. The 2.0M43 model was used in preparation of Figure 9.28.

It is readily apparent that the Q values determined for HR 729 cannot be explained completely in terms of radial modes. While the Q value for f_1 = 14.74 c/d is very close to the fundamental mode, the first overtone (H1) is absent. The second overtone (H2) could be present in the data by f_3 = 24.00 c/d but it is difficult to understand how the fundamental and second overtone could be excited while excluding the first overtone. An equally valid solution for HR 729 is that f_2 = 17.35 c/d corresponds to the l_1p_1 mode and that f_3 = 24.00 c/d is the l_2p_2 mode and that f_1 = 14.74 c/d is the fundamental mode for the star.

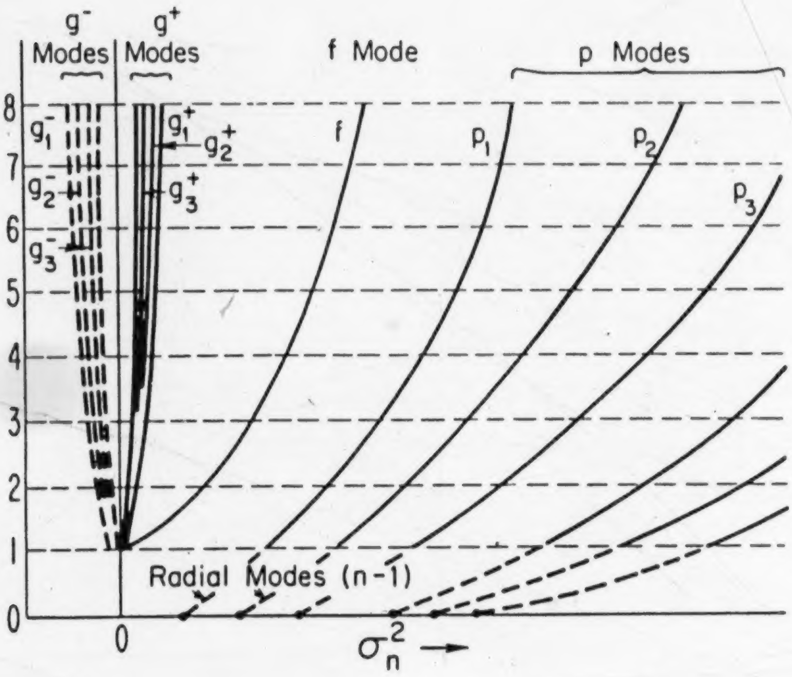

g⁻ Modes
g⁺ Modes
f Mode
p Modes
g_1^-
g_2^-
g_3^-
g_1^+
g_2^+
g_3^+
f
p_1
p_2
p_3
Radial Modes (n-1)
0
1
2
3
4
5
6
7
8
ℓ
0
σ_n^2

Figure 9.27 Schematic representation of the infinite spectrum of frequencies of oscillation for different l values and p-modes and

Possible Q Values for HR 729

$\log Q_i = -6.454 + \log P_i + 0.5\log g + 0.1M_{bol} + \log T_{eff}$
$\log g = 4.1 \pm 0.1$
$M_{bol} = 2.0 \pm 0.3$
$\log T_{eff} = 3.9 \pm 0.01$

Frequency (c/d)	Q (days) ± 0.003
14.74	0.0333
17.35	0.0284
24.00	0.0205

Possible Q Values for KW 207

$\log Q_i = -6.454 + \log P_i + 0.5\log g + 0.1M_{bol} + \log T_{eff}$
$\log g = 4.0 \pm 0.1$
$M_{bol} = 1.5 \pm 0.3$
$\log T_{eff} = 3.9 \pm 0.01$

Frequency (c/d)	Q (days) ± 0.003
16.34	0.0241
16.53	0.0239
16.70	0.0236
19.20	0.0205

Table 9.11 Pulsational Q values for HR 729 and KW 207.

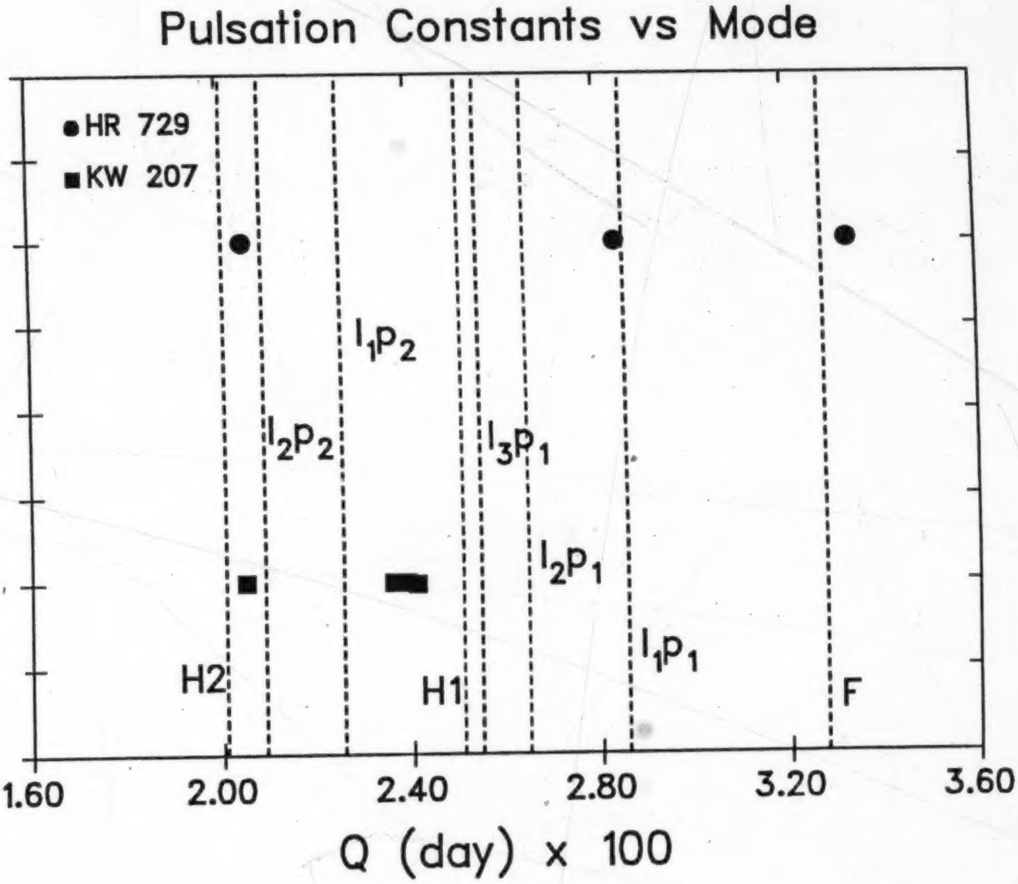


Figure 9.28 Pulsation constants for HR 729 and KW 207 plotted against various modes predicted by Fitch's 2.0M43 grid.

For KW 207 the Q values for $f_1 = 16.34$ c/d and $f_4 = 19.2$ c/d suggest that the first and second overtones are present. The period ratios for f_1 and f_4 however, do not agree with the period ratio of 0.815 appearing in Table 9.10. An alternate possibility is that m mode splitting is occurring and that the $f_1 = 16.34$ c/d and $f_4 = 19.2$ c/d frequencies are the result of the splitting of the l_1p_2 mode. If the expression for first order rotational splitting

$$\nu_m - \nu_0 = -m(1-C)\Omega \tag{9.25}$$

is used, where C is a model dependent constant(24) and is the rotational frequency for the star, then the l_1p_2 mode should be situated at a frequency of $(f_4+f_1)/2 = 17.77$ c/d which implies a Q value of 0.0222 days and agrees very well with the value of 0.02255 days given by Fitch's 2.0M43 model. A test of this hypothesis may be provided by considering the rotational velocity such an m mode splitting would imply for KW 207. By rearranging equation 9.24 an approximate value for becomes:

$$\Omega = -\frac{\nu_m - \nu_0}{m(1-C)} \tag{9.26}$$

Adopting a value of $C = 0.15$(25) and inserting the appropriate values for frequency implies that the rotational velocity for KW 207 should be on the order of 165 km/s. This is reasonable and consistent with the suggestion that KW 207 is a fast rotator. In the same vein, it is possible to associate $f_3 = 16.70$ c/d with an $m = -1$ mode splitting of l_3p_1. When this is done the Q value predicted for l_3p_1 agrees with the Fitch 2.0M43 model to within better than 1%. The remaining $f_2 = 16.53$ c/d frequency matches (to within the errors quoted for the observational Q values) the 1st overtone. While this scenario provides a possible identification of the frequencies observed for KW 207, it does suffer from a degree of ad hocness. The absence of both the l_1p_2 and l_3p_1

frequencies from the observed set of frequencies is far from satisfying. It should be pointed out that other cases do exist in the literature$^{(26)}$ where similar situations occur and the absence of a term is ascribed to the low amplitude of that term.

9.5 Conclusions

Table 9.12 summarizes the frequency identification suggested for HR 729 and KW 207. Whether these identifications or the frequencies themselves are reliable can only be determined over time and through the coordinated efforts of international observing campaigns. The subtleties of many of the features in a nonradially oscillating δ-Scuti star demand the highest of precision in frequency determination. Rather than speculate further on the present data it would be best to heed the sage advice of Publilius Syrus:

Observation, not age, brings wisdom.

Mode Identification HR 729

frequency (c/d)	mode
$f_1 = 14.74$	fundamental
$f_2 = 17.35$	l_1p_1, $m = 0$
$f_3 = 24.00$	l_2p_2, $m = 0$

Mode Identification KW 207

frequency (c/d)	mode
$f_1 = 16.34$	l_1p_2, $m = +1$
$f_2 = 16.53$	1st overtone
$f_3 = 16.70$	l_3p_1, $m = -1$
$f_4 = 19.20$	l_1p_2, $m = -1$

Table 9.12 Mode identification for HR 729 and KW 207. Modes associated with negative m values are prograde modes.

Notes Chapter Nine

1. Eggen. O.J. 1956, **P.A.S.P., 68,** 238.
2. Breger, M. 1979, **P.A.S.P., 91,** 539.
3. see review article by Douglas Gough, 1987, "Seismological measurement of stellar ages", **Nature, 326,** pp. 257 - 259.
4. Among the most common techniques of period analysis are:
   (1) the Fourier methods used in this thesis.
   (2) Phase Dispersion methods such as the Lafler-Kinman or Stellingwerf techniques.
   (3) Nonlinear least squares fitting procedures.
5. The basic forms for the DFT and the algorithm used to compute it are modifications of those appearing in the 1975 paper by Deeming, "Fourier Analysis with Unequally Spaced Data", **Astrophysics and Space Science, 36** (1975), pp. 137-158.
6. The convolution theorem of Fourier analysis states that the Fourier transform of a product of functions in the time domain will be equal to the convolution of the respective transforms in the frequency domain. Symbolically,

   $$F(\nu)*D(\nu) = \int_{-\infty}^{+\infty} F(t)D(\nu-t)dt$$

   In order to reconstruct $F(\nu)$ it is necessary to de-convolve the Fourier transform with the spectral window.
7. A possible exception is provided by observing sites situated in extreme polar regions. University of Florida has recently established a continuous variable star monitoring station at the U.S. Amundsen-Scott South pole station (latitude 90S). See David Smith, "An Observatory at 90 South". **Sky and Telescope, Vol 77, No. 6,** June 1989, pp. 598-602.
8. **M. Breger et al. Delta Scuti Newsletter, Issue 1, October 1989, pg 4.**
9. Michel Breger has pioneered in the area of international campaigns on δ-Scuti star observations. see Breger, M. et al."Multiple close frequencies of the Delta Scuti star θ^2 Tau". **Astronomy and Astrophysics, 175,** 1987, pp. 117-124.
10. Breger, M. et al."Multiple Frequencies of the δ-Scuti Variable 4 CVn". **Astronomy and Astrophysics**, pre-print 1989.
11. Jeffrey D. Scargle. "Studies in Astronomical Time Series Analysis. II. Statistical Aspects of Spectral Analysis of Unevenly Spaced Data. **The Astrophysical Journal, 263,** pp 835-853, 1982.
12. White noise is noise which appears distributed across the entire noise spectrum without any frequency dependence - ie. it is truly random. No natural process can be strictly white wrt noise since that would imply infintely fast variation in the quantity being measured. In a more practical sense astronomical photometry

introduces many noise sources that are frequency dependent. White noise should be taken to mean noise which, after removal of any obvious frequency dependent effects, appears to be a normally distributed noise. Photon arrival rates and short term atmospheric effects would satisfy this definition.

13. Matthews, J.M., Kurtz, D.W. and Wehlau, W.H. "The Rich p-Mode Spectrum of the Rapidly Oscillating Peculiar A Star HD 60435". **The Astrophysical Journal, 313,** 1987, pp. 782-791.
14. Tukey, J.W. Spectral Analysis of Time Series., ed. B. Harris. New York: Wiley, 1967, pp. 25-46.
15. Breger (private communication) suggested these frequencies but cautioned that they are likely unreliable.
16. This point has been published by D.P. Hube and the author. See Martin, B.E. and Hube, D.P. **Information Bulletin on Variable Stars. no. 3324,** 1989.
17. A more realistic treatment of stellar pulsation leads to the Linear Adiabatic Wave Equation (LAWE):

$$r_o\ddot{\zeta} = \zeta 4\pi r_o^2 \frac{d}{dm}[(3\Gamma_{1,0} - 4)P_o] + \frac{1}{r_o}\left(16\pi^2\Gamma_{1,0}P_o\,\rho_o\,r_o^6\,\frac{\partial\zeta}{\partial m}\right).$$

    Solutions to this equation are obtained numerically by integrating outward from the stellar center to the surface. The LAWE has an infinite number of solutions corresponding to the fundamental and overtone modes of oscillation.
18. Stellingwerf, R.F. 1979, **The Astrophysical Journal, 227,** pg 935.
19. Wolff, S.C. 1983. The A-Stars: Problems and Perspectives. Washington D.C.: NASA Scientific and Technical Branch, pg 104.
20. see Fitch, W.S. 1980, Nonradial and Nonlinear Stellar Pulsation. ed. H.A. Hill and W. Dziembowski. Berlin:Springer Verlag, vol. 125, pg 7.
21. see Cox, J.P. 1980. Theory of Stellar Pulsation. Princeton: Princeton University Press, pp. 242-245. Cox provides tables for nonradial p-modes for the l=2 case. His models are for polytropic stellar models.
22. reference 10, pg.5.
23. Fitch, W.S. 1981, **The Astrophysical Journal, 249,** pp. 218-217.
24. The constant C is often referred to as Ledoux's constant and depends on both the structure of the star as well as the mode of oscillation. It is usually a small quantity, less than one.
25. Kurtz, D.W. 1982, **Monthly Notices of the Royal Astronomical Society, 200,** pg 821.
26. see reference 10, pg 6.

Chapter Ten
A Search for Rapid Variability in Peculiar A Type Stars

10.1 Introduction

The peculiar A (= A_p) stars comprise a group of stars of spectral type A through early F which show peculiar abundances of some metals as well as strong magnetic fields. While it has been known for some time that a significant number of peculiar A stars are variable with periods from hours to a few days, it has recently been discovered(1) that some stars of this class vary in low amplitude, multiple modes with periods of 15 minutes or less. Such rapid variations are usually interpreted as evidence of high order nonradial p-mode oscillations. To date only a handful of such rapidly oscillating A_p (roA_p) variables have been identified - mostly among southern hemisphere stars(2).

Unambiguous identification of these stars and their periods would provide very useful constraints on current models of stellar structure. In cases where rotational splitting of some oscillatory modes is evident, constraints may also be placed on rotational velocities and magnetic field structure for the star.

The extent of the rapid oscillation phenomenon - with respect to spectral class, temperature etc - is poorly understood. Do the roA_p stars form a distinct instability strip on the HR diagram as do many other variable stars? To date it is known that the roA_p stars tend to be cool (A5 - early F) A_p stars that show enhanced abundances of strontium, chromium and europium. What is not clear is why the roA_p phenomenon favors this highly specific type of star (if, it in fact, does at all), how common the roA_p phenomenon is among cool A_p Sr-Eu-Cr stars and what ultimately gives rise to the roA_p phenomenon(3).

To help address some of these questions, a photometric search for rapid oscillation among A_p stars was begun in the fall of 1986. The results of this survey - presented below - were inconclusive and the project was terminated in the fall of 1987.

10.2 The Program Stars

The stars selected for the search for the roA_p effect were required to satisfy at least one of the following criteria:

1. A_p - F_p classification
2. known delta Scuti behaviour
3. late A - early F
4. no brighter than V = 4.5.

While the first criterion is obvious the second one deserves comment. It is known that the roA_p stars share the same region of the HR diagram with δ-Scuti variables. Is there a connection between these groups? In other words, is there a continuum of pulsation periods between the 5 minute "roA_p regime" to the 1 hour regime of δ-Scuti stars? The third criterion would include any cool A - F star and especially those with abundances anomalies - not only those with strong magnetic fields. The last criterion was a "system" imposed constraint since dead time losses in the photometer and electronics would become significant at a brightness exceeding 4.5 magnitudes. Table 10.1 summarizes the program stars selected for this study.

10.3 Method of Observation

Observations were carried out using the two channel photometer on the Devon 0.5 m reflecting telescope. Prior to September 1987 only one channel of the photometer was used. Observations were confined to the B or V bandpass regions. Typical integrations were of 10 - 20 second duration.

Name	Spectral Type	V
HR 478	$A0_pSiSr$	5.59
HR 707	$A5_pSrEu$	4.52
HR 2564	$F0V_p$	4.65
HD 32655	$F2II_p$	6.20
HR 1971	$A2V_pCr$	5.47
HR 1974	A3 DELTA DEL	6.58
HD 43244	F0V	6.52

Table 10.1 The program stars used in the search for rapid oscillations.

An observing run usually consisted of a continuous, long string of integrations of the program star bracketed by observations of both sky and a comparison star. Since the time scale of variation searched for was considerably less than expected changes in atmospheric transparency and seeing, classical differential photometry was not employed.

10.4 Methods of Analysis

Standard photometric reduction techniques were applied to produce light curves from each observing string. In most cases a simple first order extinction was adopted and calculated via a linear regression of the light curve with respect to airmass. The method of period analysis used was identical to that described in chapter nine.

10.5 Summary of the Observations

Photometric data were obtained on 7 program stars. These stars are listed in Table 10.1.

10.5.1 HD 32655

This was the most extensively observed of the program stars. A journal of observations for HD 32655 is given in Table 10.2. Figure 10.1 shows the light curve of HD 32655 from the exceptionally good photometric evening of November 10, 1986. There is no obvious variability present in this light curve. The Fourier transform, however, does suggest that some significant frequencies may be present in the signal. Unfortunately, the results are not stable. A comparison of transforms (Figure 10.2) undersores the ambiguity of the results. The Nov 10/86 transform spectrum is very rich, showing low frequency power significantly greater than the mean noise level as well as some high frequency signal.

Date	Time (hr)	n	σ (mmag)	Filters
Nov 10/11-86	2.37	550	2	B
Dec 8/9 -86	1.20	278	2	B
Dec 30/31-86	0.75	170	3	B
Dec 30/31-86	0.50	130	3	B
Jan 21/22-87	4.67	1200	3	B
Jan 21/22-87	1.17	300	2	B
Jan 22/23-87	1.18	300	3	B
Jan 24/25-87	4.08	1050	4	B
Jan 25/26-87	1.16	300	7	B
Total:	17.08	4278		

Table 10.2 Summary of observations of HD 32655.

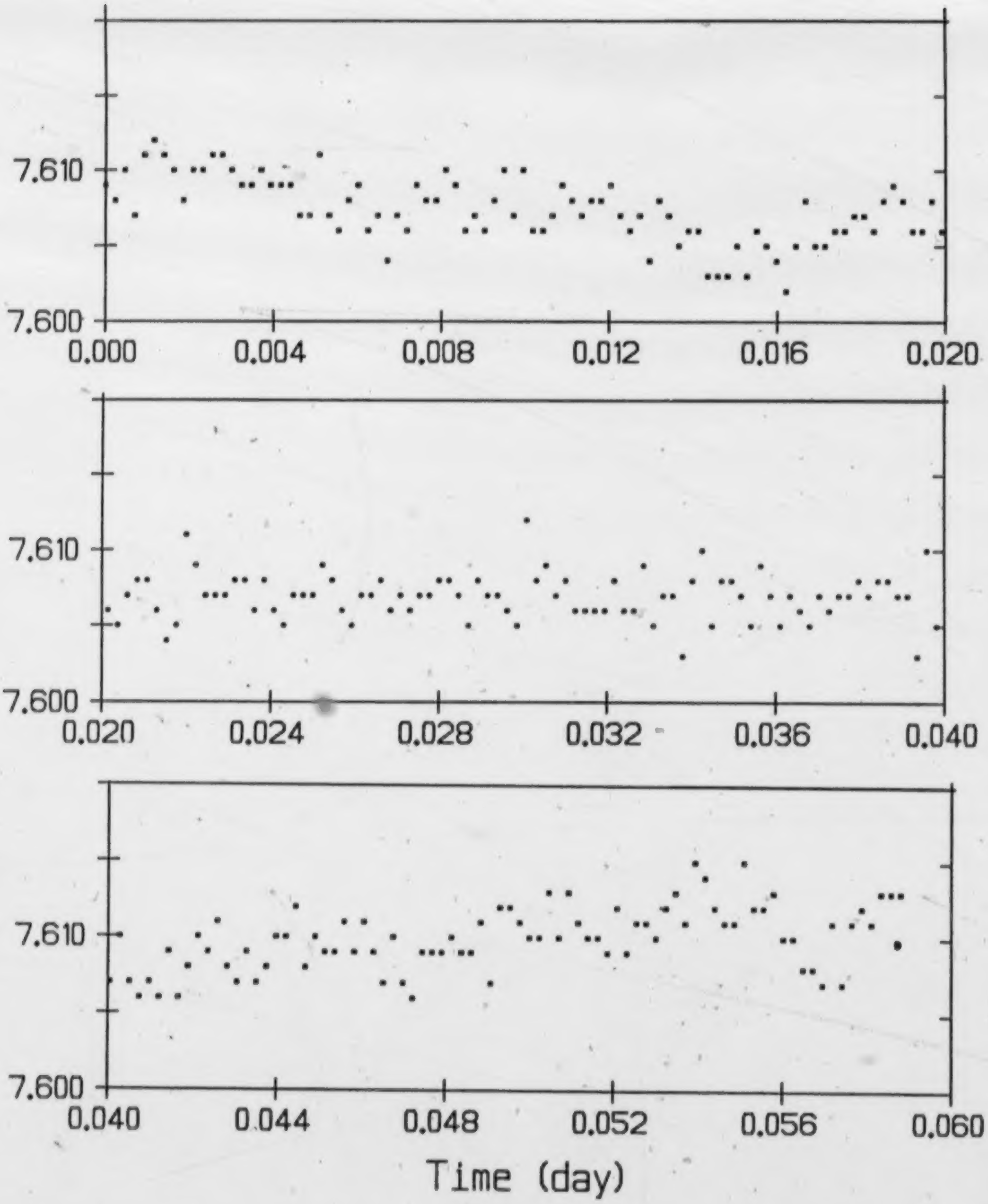


Figure 10.1 Light curve for HD 32655 in the b filter from the night of Nov10/11-86. The mean noise level in the data is 2 mmag. Δ t = 10 s.

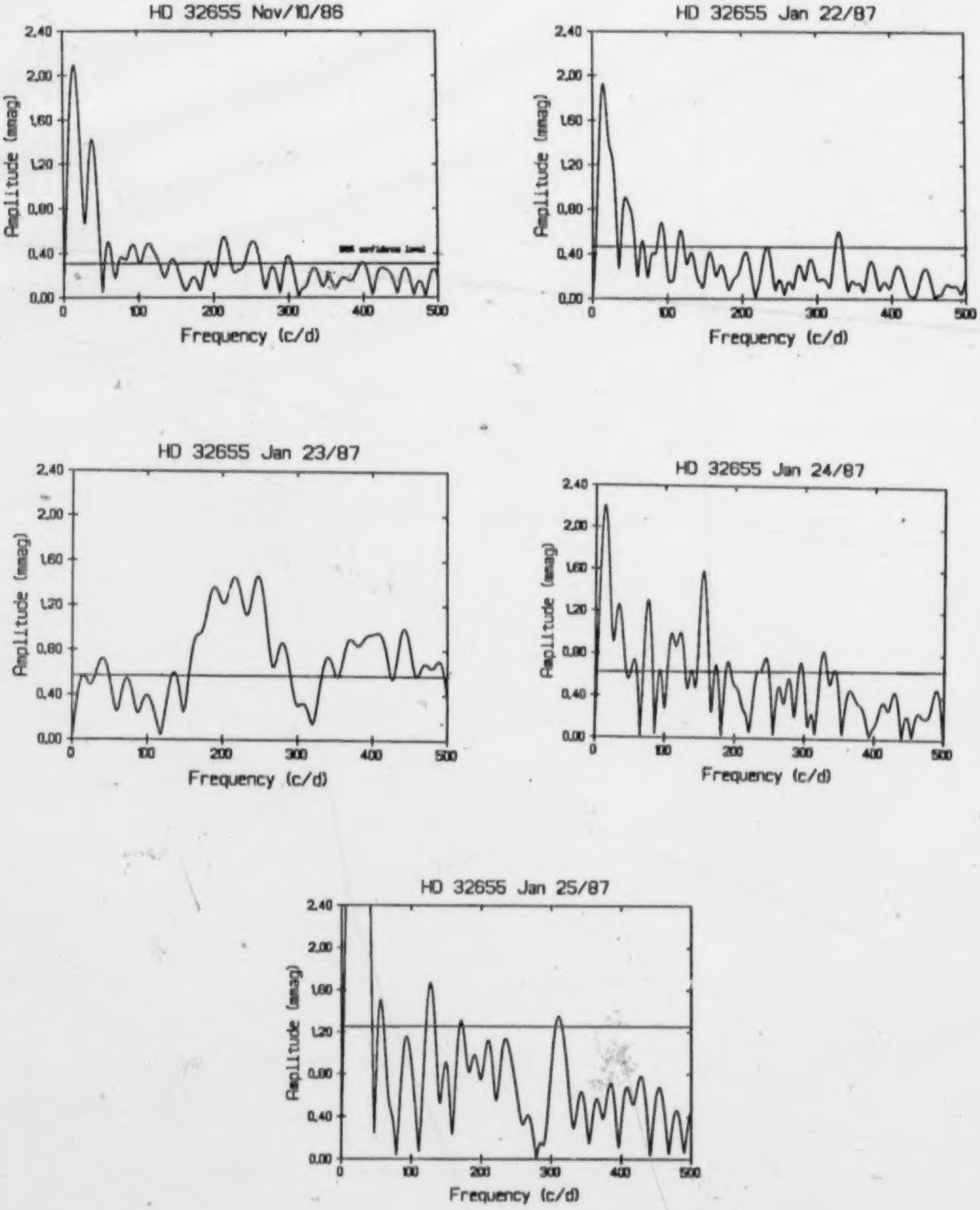


Figure 10.2 Fourier transforms for HD 32655 for the nights: Nov 10/86, Jan 22/87, Jan23/87, Jan24/87 and Jan 25/87. The 99% confidence level for each transform appears as a horizontal line. There are no stable features appearing in all transforms.

The low frequency power is not as evident on the Jan 23/87 transform but reappears on both the Jan 23/24 and Jan 24/25 transform spectra. There do not appear to be any consistent high frequencies present in all of the transforms. After more than 17 hours of observation of this star no clear evidence for roA$_p$-type behavior had been found.

10.5.2 HR 1971

The journal of observations for HR 1971 is given in Table 10.3. A sample light curve for HR 1971 appears in Figure 10.3 with Fourier transforms shown in Figure 10.4. A comparison of transforms from Nov 23/86, Feb 2/87 and Feb 20/87 suggests that there may be signal concentrated at approximately 330 c/d. This corresponds to a period of 4.36 minutes which is consistent with roA$_p$ behavior. Unfortunately, this feature is not stable in the data. It is premature to speculate whether or not these are real periods until further data have been collected.

10.5.3 HR 478, HR 707, HR 1974, HR 2564, and HD 43244

The journal of observations for the stars HR 478, HR 707, HR 1974, HR 2564 and HD 43244 is given in Table 10.4. No significant feautures appear in either the light curves themselves or the Fourier transforms computed for these stars.

10.6 Conclusions

The attempt to detect rapid light variations in the seven program stars was terminated by the fall of 1987. No clear evidence of roA$_p$ behavior was found in any of the stars and it soon became clear that a search of this type would require an enormous amount of observing time. HD 32655 is a case in point. After 17 hours of observation the null hypothesis - that the star is **not** a rapid oscillator - seems the most reasonable. A survey of this type must inescapably face the problem that while an observation confirming the rapid variability of a star may require only several hours of observation on several nights, the converse requires far more observation to establish with reasonable confidence.

Date	Time (hr)	n	σ (mmag)	Filters
Oct 22/23-86	1.21	272	2	V
Nov 23/24-86	0.72	258	2	B
Dec 3/4 -86	1.40	232	7	B
Dec 5/6 -86	1.62	360	2	B
Feb 2/3 -87	2.14	550	5	B
Feb 20/21-87	3.79	978	4	B
Total:	10.88	2650		

Table 10.3 Summary of observations of HR 1971.

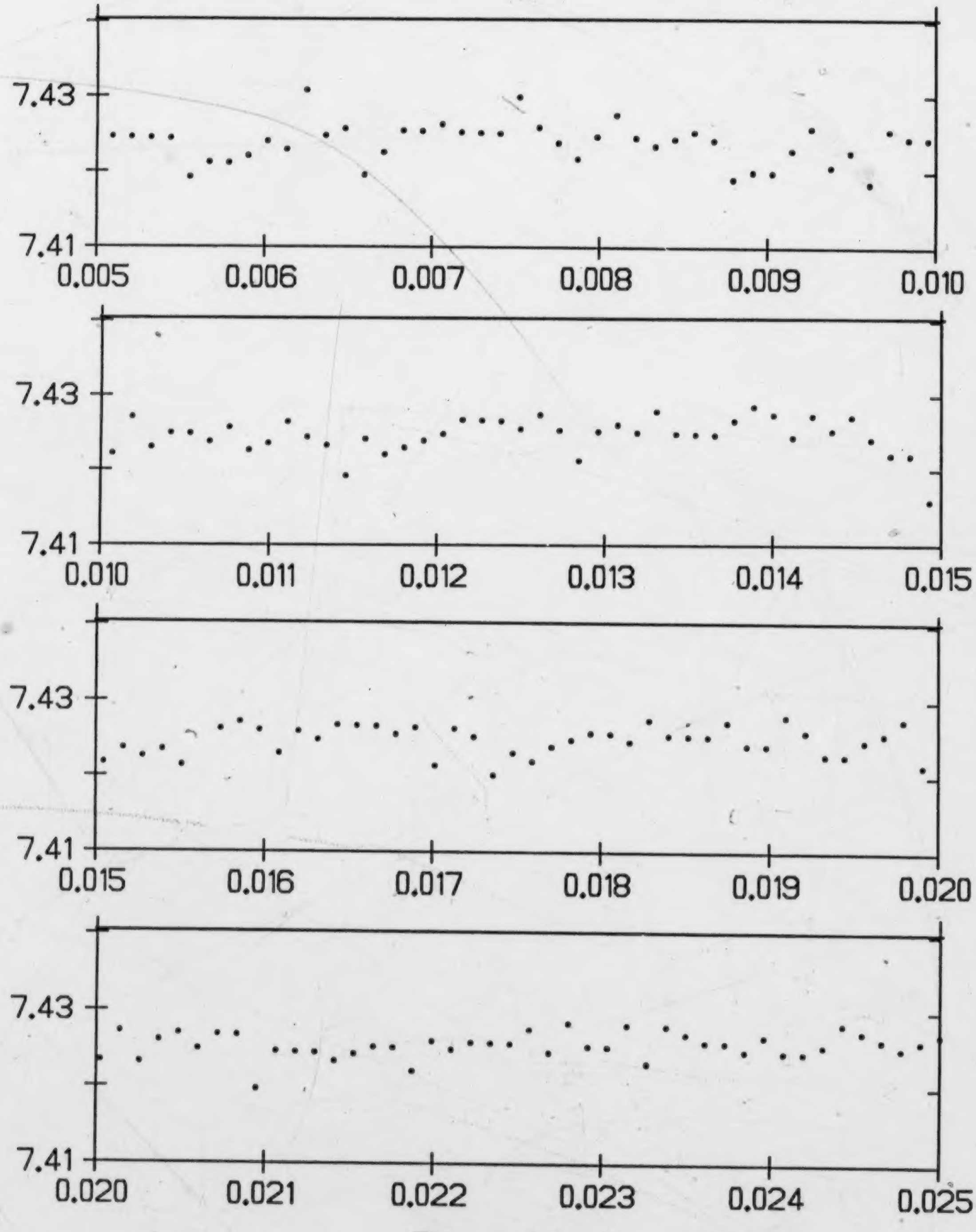


Figure 10.3 Light curve for HR 1971 in the b filter from the night of Nov 23/24-86. The mean noise level in the data is 2 mmag. Δ t = 10 s.

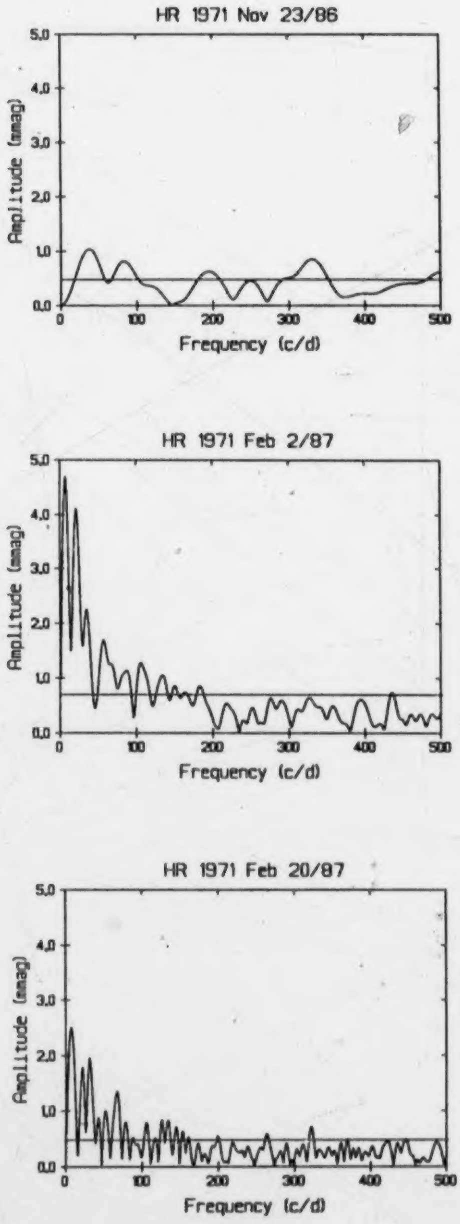


Figure 10.4 Fourier transforms for HR 1971 for the nights Nov23/86, Feb2/87 and Feb20/87. The 99% confidence level for each transform appears as a horizontal line. A small feature is present and above the 99% level at 330 c/d for the transforms of Nov23/86 and Feb20/87. A similar feature appears in the Feb 2/87 transform.

Date		Time	n	σ	Filters
HR 478		(hr)		(mmag)	
	Oct 18/19-86	0.68	120	2	V
	Oct 22/23-86	2.40	300	3	B
	Total:	3.08	420		
HR 707					
	Oct 14/15-86	1.55	300	3	V
	Total:	1.55	300		
HR 1974/					
	Jan 8/9 -87	0.97	218	3	B
	Total:	0.97	218		
HR 2564					
	Dec 2/3 -86	1.60	360	3	B
	Dec 3/4 -86	0.93	210	2	B
	Dec 5/6 -86	0.91	204	2	B
	Feb 2/3 -87	1.83	550	3	B
	Feb 20/21-87	3.31	850	5	B
	Total:	8.58	2174		
HD 43244					
	Jan 6/7 -87	1.78	400	2	B
	Total:	1.78	400		

Table 10.4 Journal of observations for HR 478, HR 707, HR 1974, HR 2564 and HD 43244.

Notes Chapter Ten

1. The prototypical roA$_p$ star is HD 101065 - referred to as Pryzbylski's star. D.W. Kurtz made the serendipitous discovery that HD 101065 oscillated with a period of approximately 12.5 minutes and an amplitude of less than 10 mmags. The earliest papers on roA$_p$ stars are:
    i. Kurtz, D.W. 1980, **Monthly Notices of the Royal Astronomical Society, 191,** 115.
    ii. Kurtz, D.W. 1981, **Monthly Notices of the Royal Astronomical Society, 196,** 61.
    iii. Kurtz, D.W. 1982a, **Monthly Notices of the Royal Astronomical Society, 200,** 807.
    iv. Kurtz, D.W. 1982b, **Monthly Notices of the Royal Astronomical Society, 200,** 503.
    v. Kurtz, D.W. 1983a, **Monthly Notices of the Royal Astronomical Society, 202,** 1.
    vi. Kurtz, D.W. 1983b, **Monthly Notices of the Royal Astronomical Society, 205,** 3.
2. To date only 12 stars have been identified as rapidly oscillating A$_p$ stars. They are summarized in:
   Warner, B. 1988. High Speed Astronomical Photometry. Cambridge University Press: Cambridge, pp. 236-237.
3. The currently favored model for the roA$_p$ effect invokes the oblique pulsator model in which the axis of symmetry for pulsation is the magnetic axis of the star which is aligned obliquely with the rotational axis. The very rapid light variation is explained in terms of high overtone p-modes.

Epilogue

Personal Reflections on Science Teaching

Occasionally I'm asked if I am a teacher with a passion for astronomy or an astronomer with a commitment to teaching. Such questions are dichotomizing and in answering them it is all too easy to fall into an either-or mode of expression. I am a teacher, but only because I am also an astronomer. Both teaching and astronomy form part of my life-world and each interacts with the other in an organic fashion.

Although the memory has faded, I still remember the excitement I felt when I peered through a telescope for the first time. The telescope belonged to an older brother (to whom this thesis is dedicated) and I was five or six at the time. That a small point of light became, in the eyepiece, a planet with rings was an extravagant event and I was enthralled by it. As I grew so did my passion for the night-time sky. By the time I had reached high school a succession of small telelscopes (none of them very good!) had been built. During this time a new pleasure had emerged - others were genuinely interested in the astronomy that I was doing. The sharing of astronomy seemed to be a natural part of the doing of astronomy.

Although my career plans seemed well set, the paucity of employment opportunities for astronomers in the mid 1970's and a burgeoning family necessitated a change in direction. On completing an MSc in astronomy I pursued studies in education and became a high school science teacher. It was early in my career as a science teacher that the seeds of this thesis were sown.

Brimming with the excitement of a new teacher and full of "neat ideas from astronomy", I encountered some of the students described in the first chapter of this thesis. For some of my students, science was a frustrating invitation to failure. The joy and intrigue of doing science was missing from their notions of what science was. Science had become for them an extended cognitive exercise. While some students thrived on this form of school science other, apparently equally bright students did not. Some became resigned to the self-assigned labels of "non-science type" or "people persons". Science was what "scientists" did and what they (the student) had to learn. Even more depressing was my discovery that some of my teaching colleagues also felt this way. What seemed to be missing from school science was a sense of room - in a meaningful way - for the person in science.

As I puzzled over this "depersonalization" I began to suspect some of my own assumptions about what it means to teach. First, my own biography was inextricably tied to my valuing and experiencing of science. My recognition of the value of some idea or set of ideas in science, my willingness to persevere in learning difficult material is closely tied to this sense of participation in the ideas of science. What about my students? Had I seriously considered that they too might need such a sense of personal involvement in science and had I considered the form which that involvement might take?

Thus I began to look for ways in which to encourage my students to develop a personal association with science. One of the most immediate ways of "personalizing" science was to, as much as meaningfully possible, share my own passions with science with my students. Slides of a family backpacking trip became a vehicle for more than just looking at the scattering of light by aerosols in a mountain valley. The sames slides provided a model that showed that scientific ideas extend beyond the reach of the classroom - you can carry them with you on a mountain trail. As teachers, the sharing of personal experiences with students is a rewarding and mutually enriching experience. Through such sharing a context is established that challenges both the teacher and the student to examine their own lived experience in light of the science lesson at hand. It is, in a practical way, an attempt at establishing Polanyi's Society of Explorers.

Another way in which I have tried to "live" some of the ideas discussed in this thesis has been to attempt to, wherever possible, root the ideas being explored in class within the experience of the student. Thus began a project spanning nearly a decade with a colleague (Neil Spronk) that culminated in the publication of a high school physics textbook, PhysicAL: an Activity Approach to Physics. In this text the rationale is simple - ideas must be presented in as simple and experiential a manner as possible before abstraction takes place. As well, a diversity of learner styles should be attended to. This has proven to be a continual challenge in the classroom, one that is both rewarding and time consuming but one for which, I believe, there is sound pedagogical support.

Finally, I would like to submit my view of an "ideal" teacher. Such a person should have within, a sense of story, of personal engagement with science. This does not mean that the person need be a "scientist" in the common denotation of the word, but rather that teacher should hold an abiding interest in some aspect of science and hold this within the context of having a story to tell. It is this sense of story that gives the science a life-rooted and palpable quality. But a sense of story is not enough, it must also be coupled with a pedagogic orientation towards the nurturing of stories within the student. In my own teaching I strive towards an exploration of and reflection on my own sense of story and try to encourage my students to do the same. This might sound erudite and impractical but it can be as simple as challenging students to reflect on ways in which a particular concept in a lesson is related to their experience of the world. Is there a "resonance" with their stories of the world? I would like to suggest that it is through our own personal sense of story that we appropriate to ourselves ideas and concepts and make them a truly meaningful part of our life-world.

Future Directions of This Research

In Chapter 7 some of the educational directions for further research were presented. As the thesis suggests, however, I have additional astronomical research interests, that while distinct, are not entirely separate from science education. The study of ellipsoidal variable stars will, I hope, keep me "employed" for many years to come. They are a common and unduly neglected class of star. More work remains to be done on 42 Persei and there are others on which I am currently working. As well, international campaigns on Delta-Scuti stars will continue to interest me for their potential importance to stellar astronomy as well as their intrinsic challenge. While the results of the search for rapidly oscillating A_p stars were inconclusive, a long term survey of stars for this phenomenon could prove to be a useful contribution to our understanding of the rapidly oscillating A_p effect. It is within the context of the astronomical projects just described that I hope to continue to explore the some of the broad philosophical issues addressed in this thesis. Can, for example, Holton's thematic analysis be used as a tool for understanding current controversies in astronomy? As well, can the notion of personal science and the exploration of Polanyi's epistemology in relation to science education be further developed, especially as a means of understanding conceptual change? While there many other directions that future research may take, it may be wise to heed the words of Solomon

Of the making of books there is no end [!]

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